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Title:	Relativistic Magnetic Reconnection: A Powerful Cosmic Particle Accelerator
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Relativistic Magnetic Reconnection: A Powerful Cosmic Particle Accelerator

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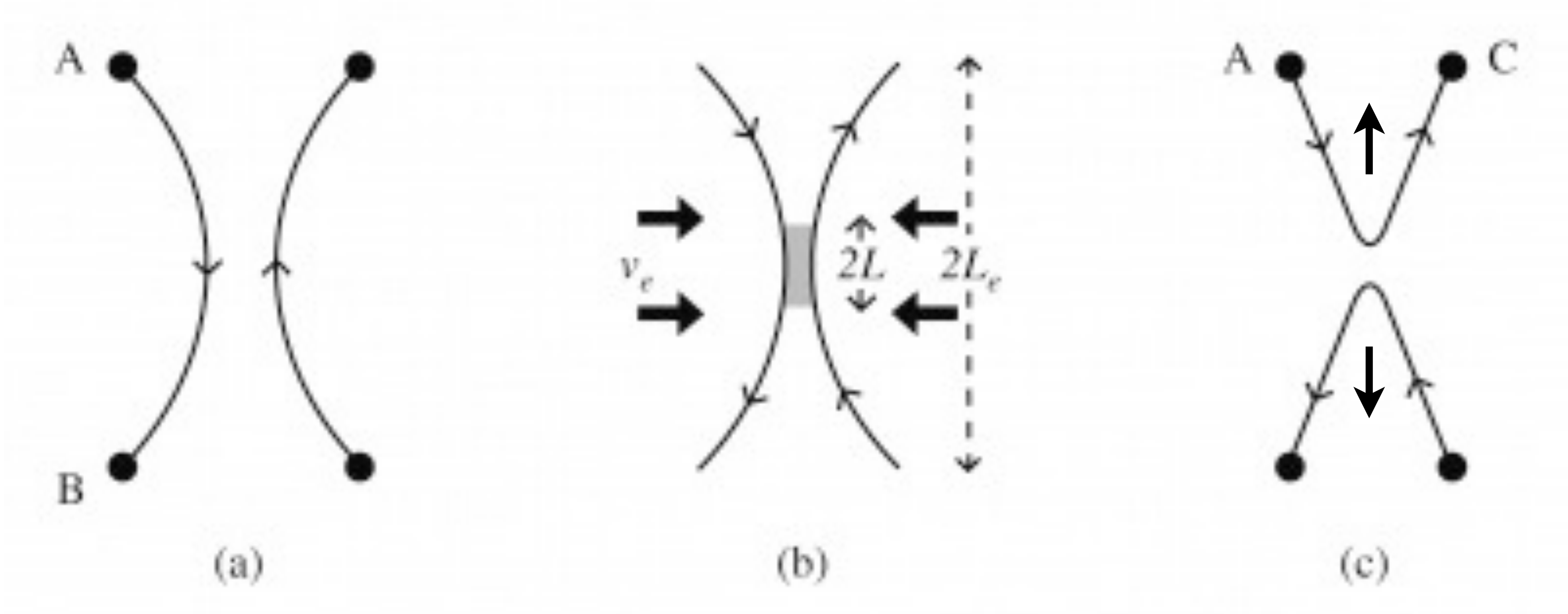
October, 6th 2014

Magnetic Reconnection & Associated Particle Acceleration



Where does reconnection occur?

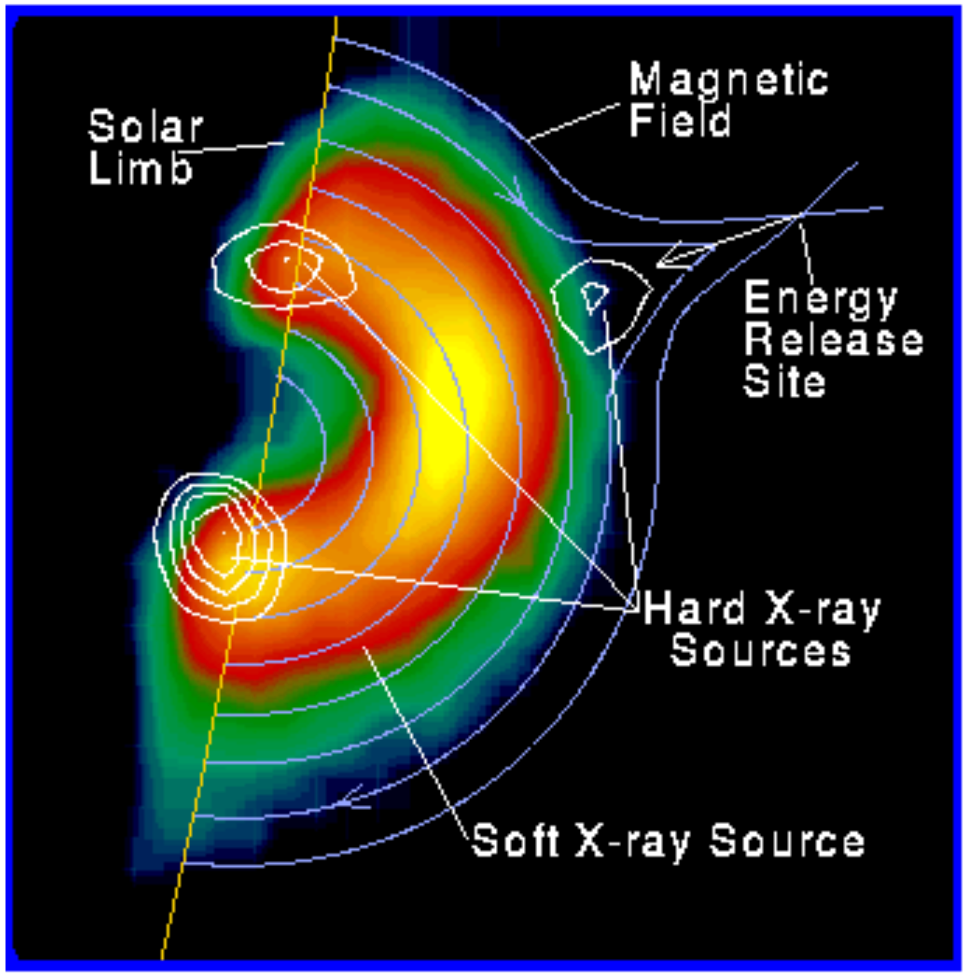
- Planetary magnetosphere, solar flares
- Active galactic nuclei (AGN), Gamma-ray bursts (GRBs), Pulsar wind nebulae (PWNs)

Particle Acceleration: Hints from solar flares

- Power-law distribution
- Most of electrons are accelerated

$N_{nonthermal} > N_{thermal}$ (e.g., Krucker et al. 2010)

This is not well understood.



This talk:

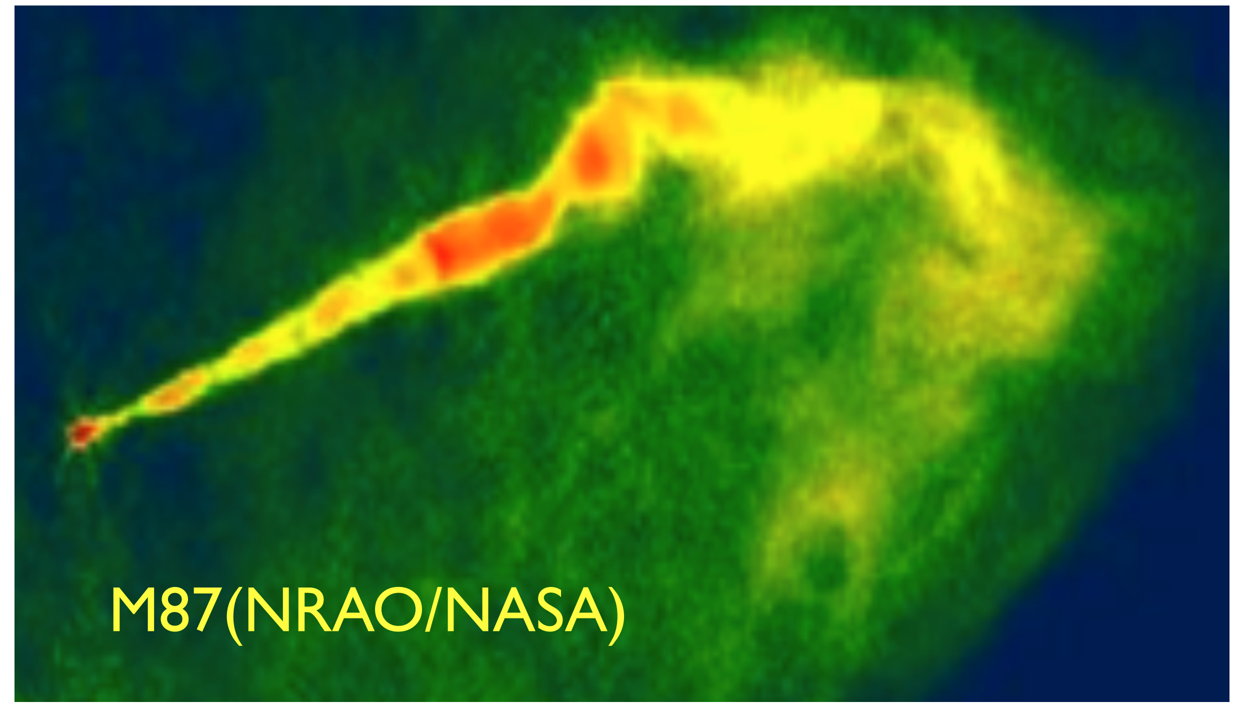
- Strong particle acceleration in relativistic reconnection with hard power-law index p~1.

- Power-law formation model including relativistic Fermi acceleration and injection.

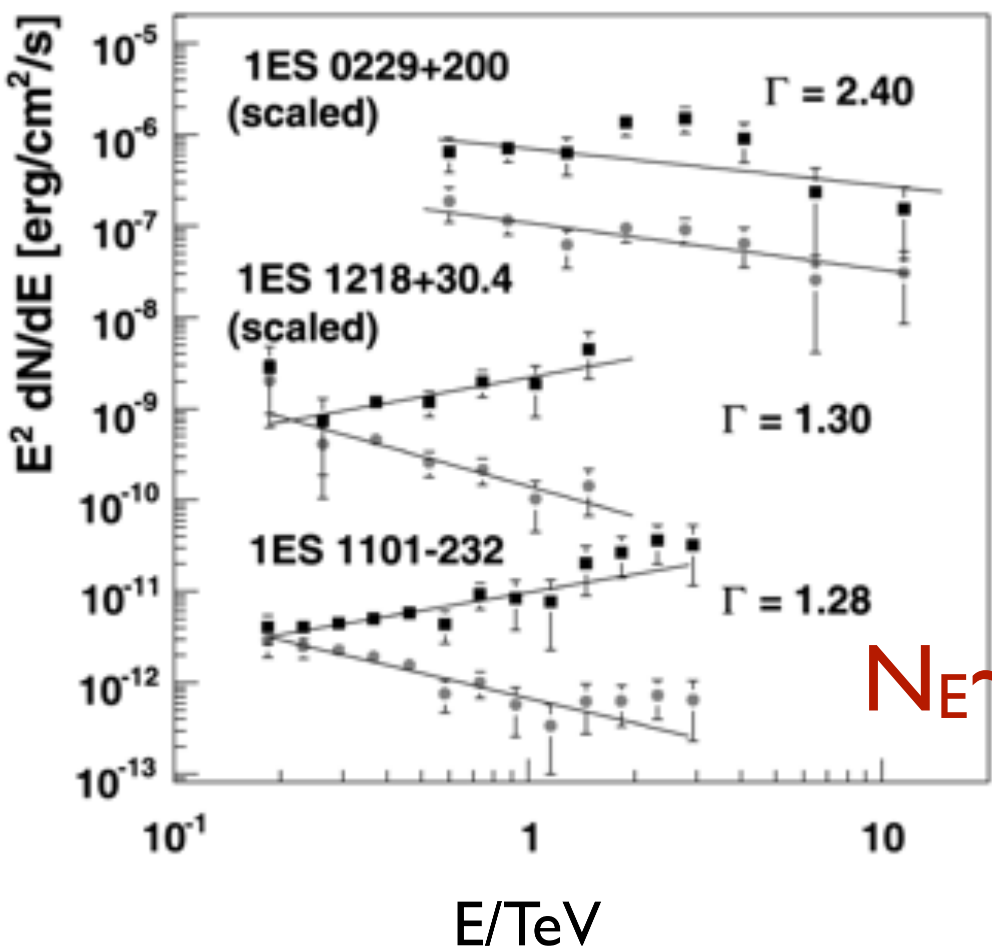
Extreme Acceleration/Radiation in AGNs, GRBs, and PWNs

In magnetically dominated model

$$\sigma = \frac{B^2}{4\pi n m c^2} \gg 1$$



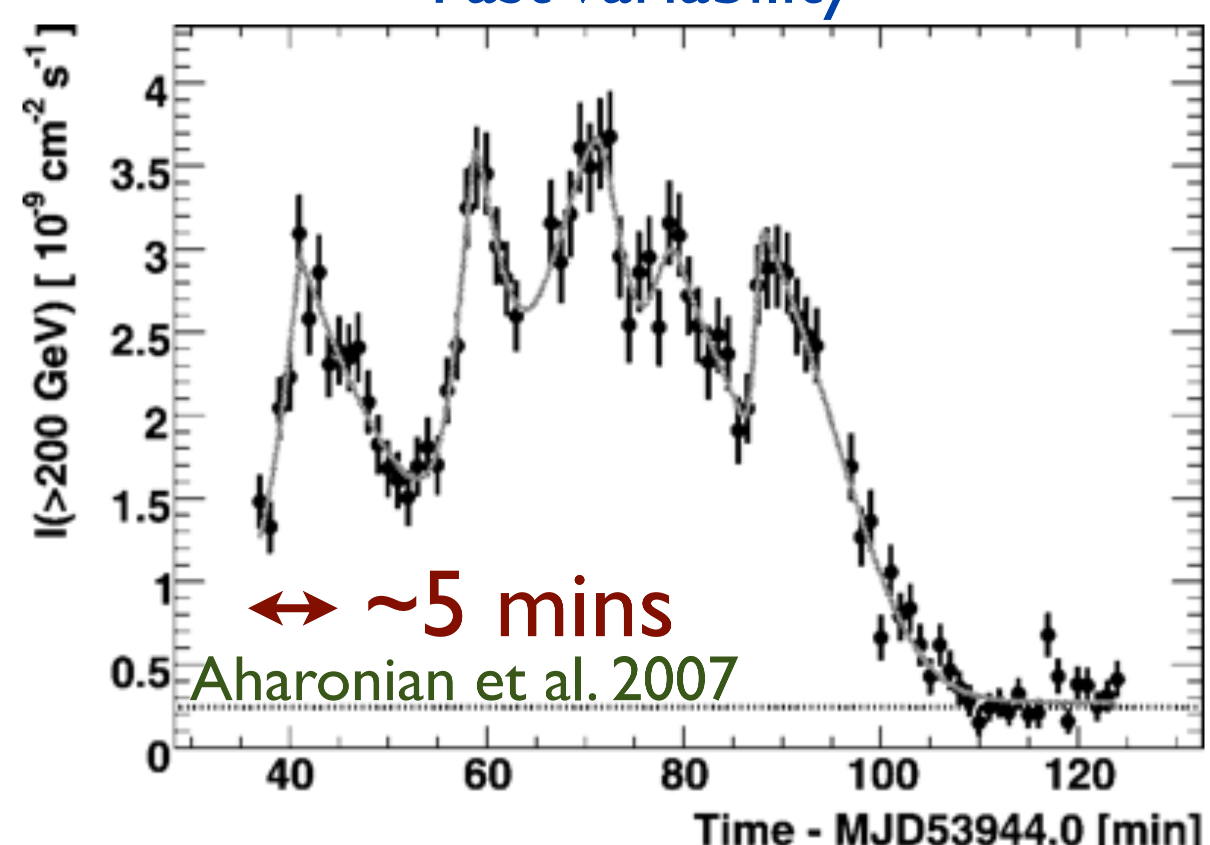
Hard Spectra



$N_E \sim E^{-1}$

Aharonian et al. 2006;
Krennrich et al. 2008

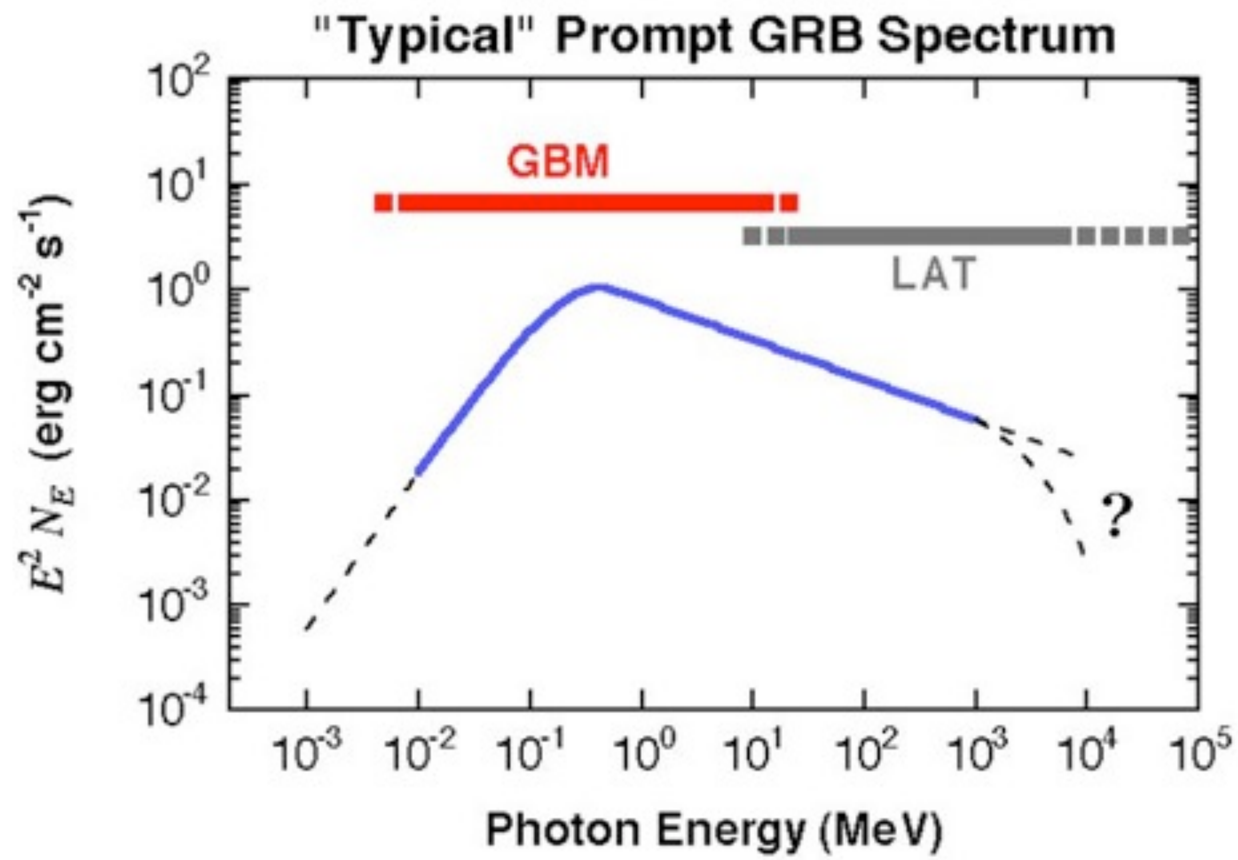
Fast Variability



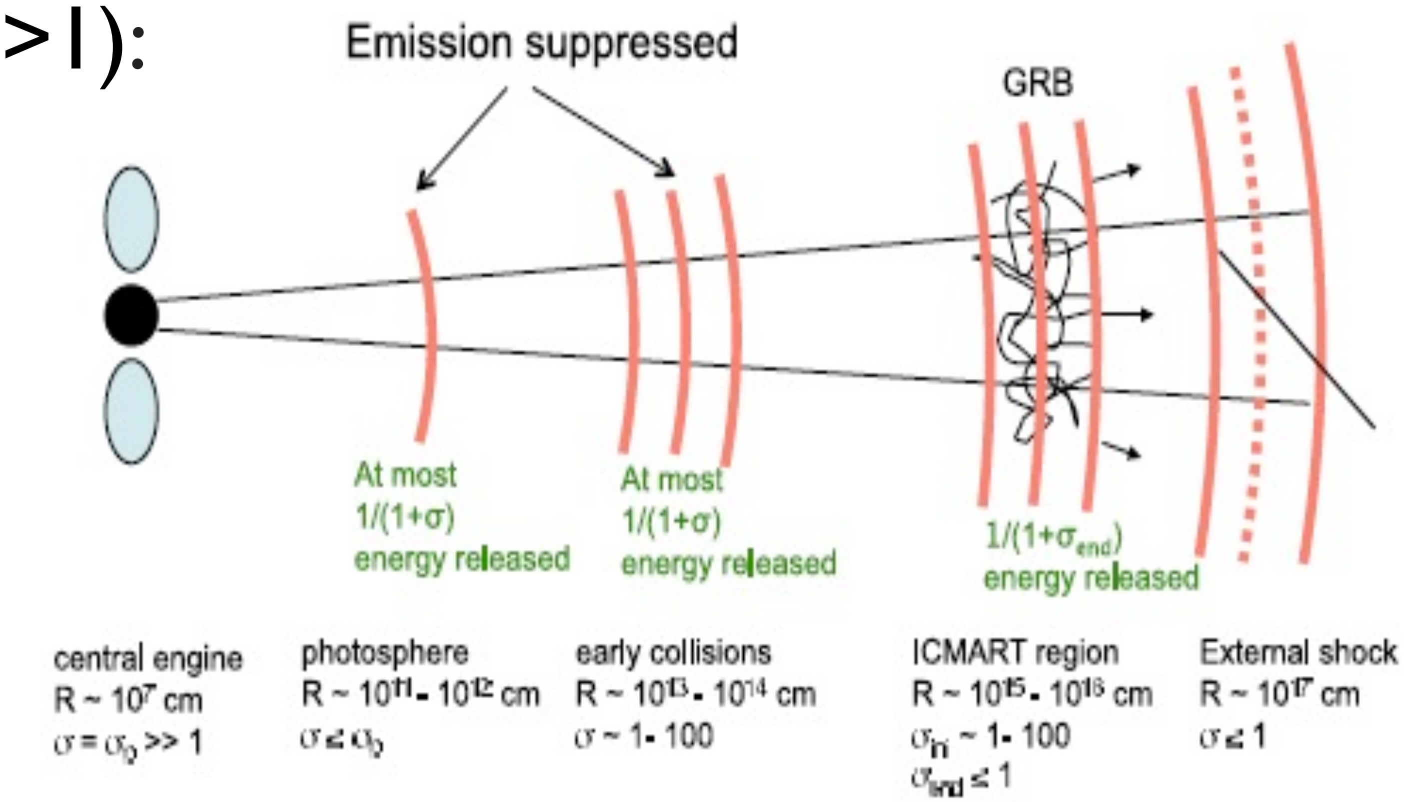
Extreme Acceleration/Radiation in AGNs, GRBs, and PWNs

• GRB Band function (Band et al. 1993)
Low energy power law $N_E \sim E^{-1}$

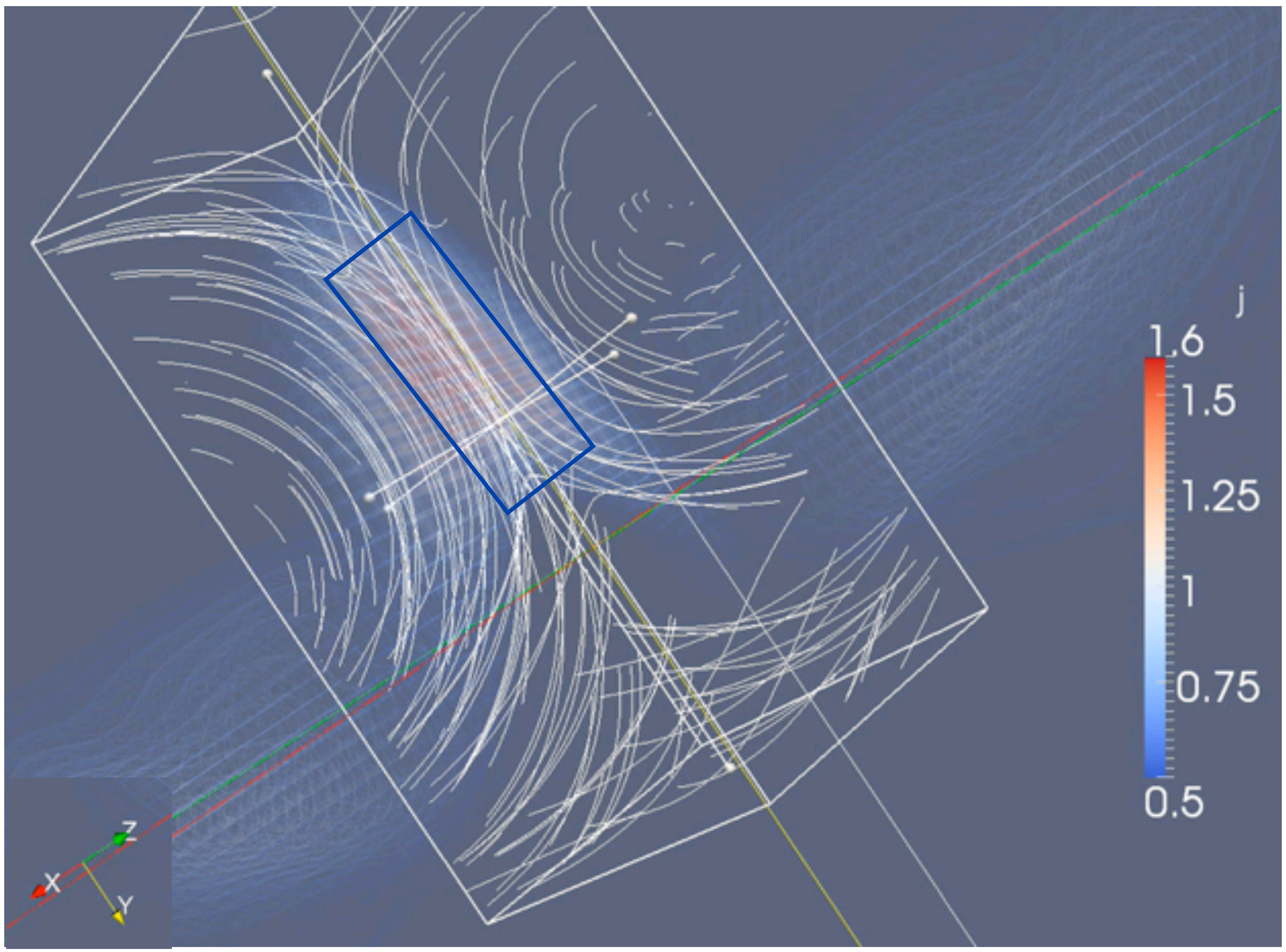
Indicating particle spectral index $p = (s+1)/2 = 1$, whereas shocks give $p = 2$

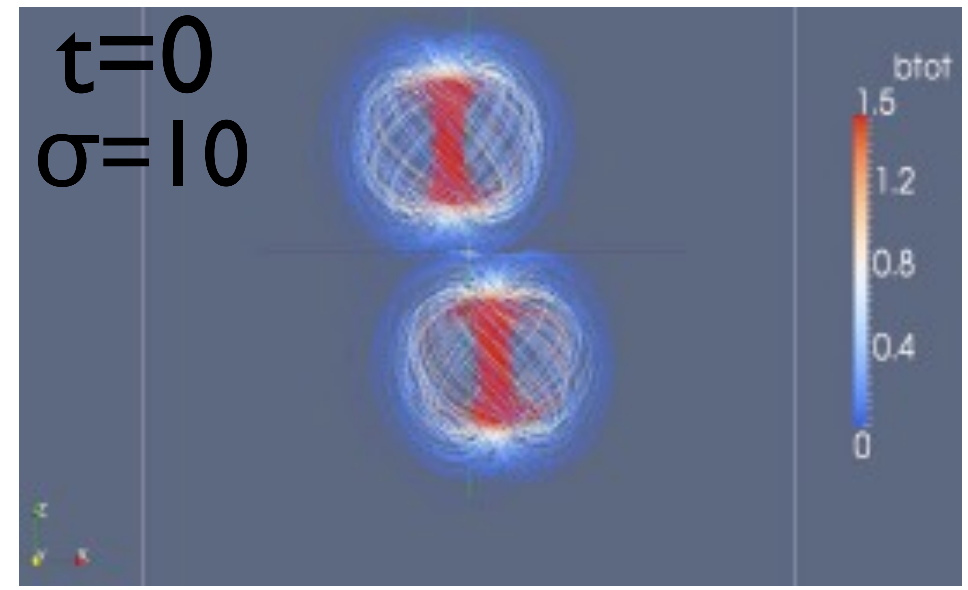


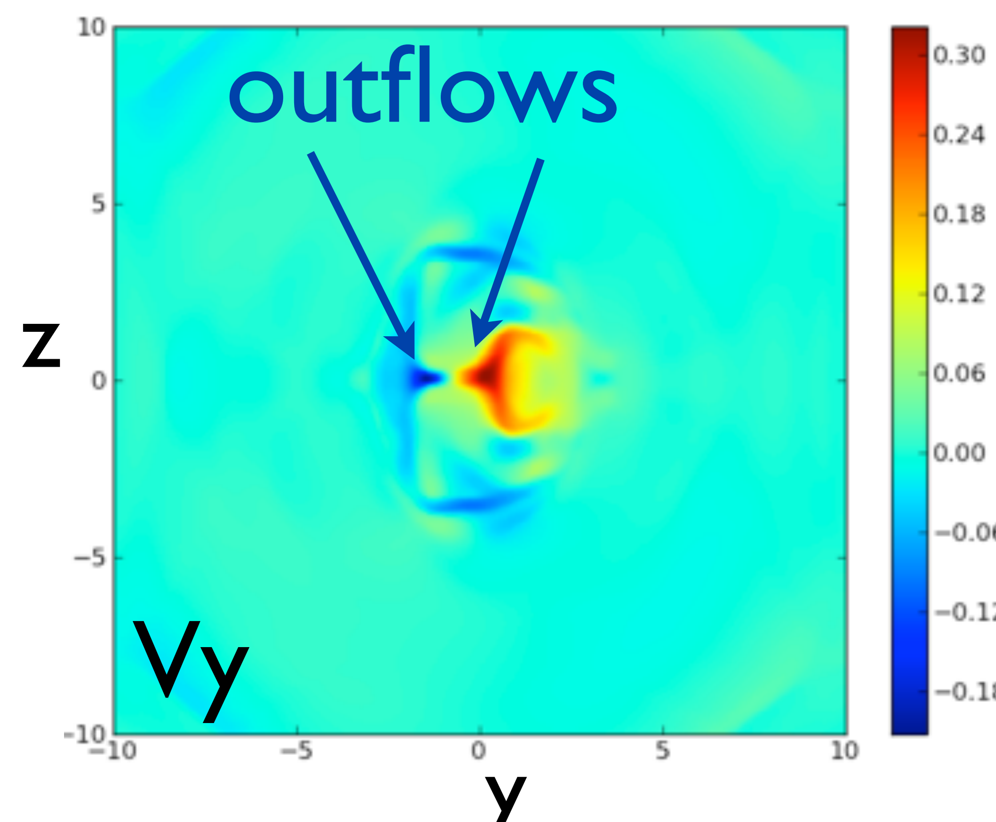
Magnetically dominated model (σ>>1):
• require a highly efficient energy dissipation
• require an efficient production of energetic particles.
(Lyutikov 2003; Zhang & Yan 2011; McKinney & Uzdensky 2012)



Collision of two magnetically dominated blobs: 3D Relativistic MHD simulations



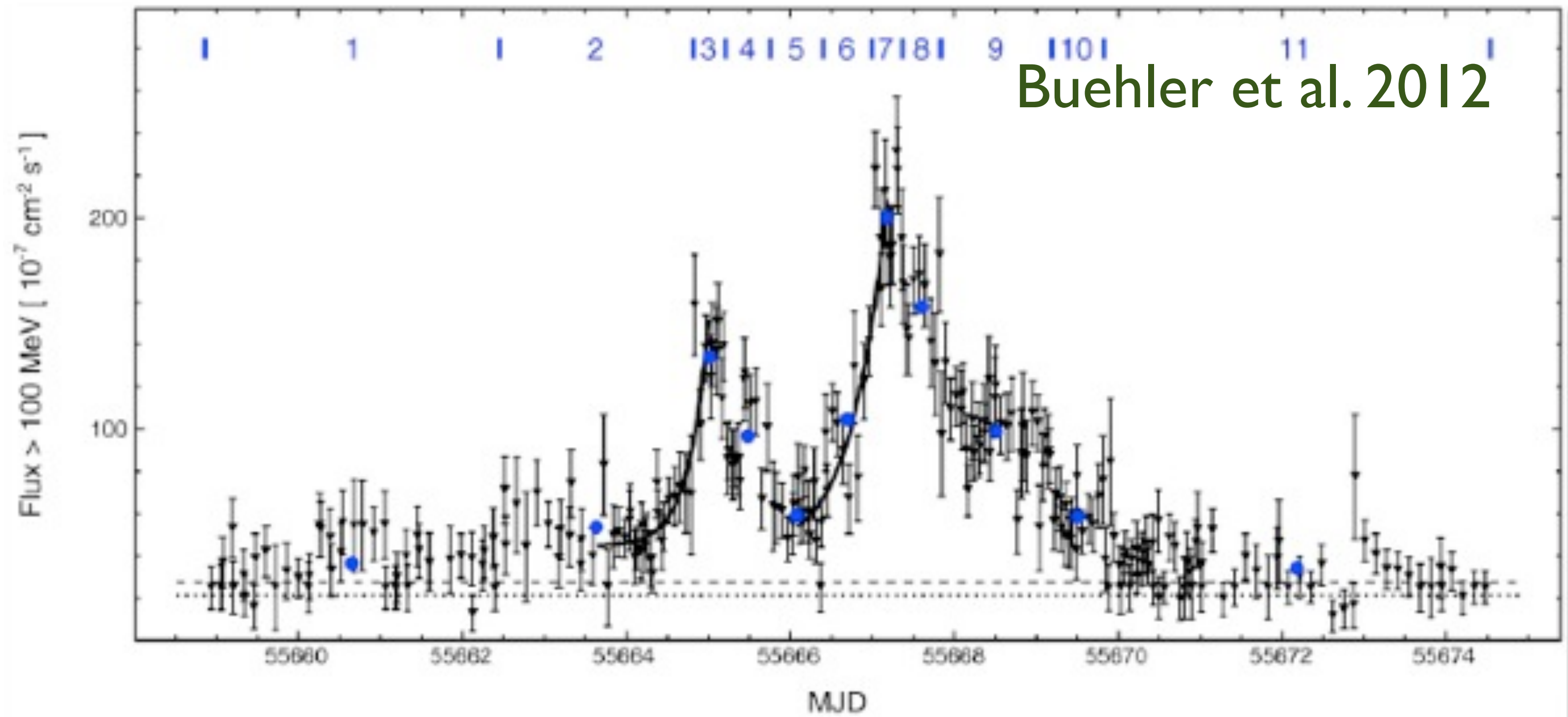


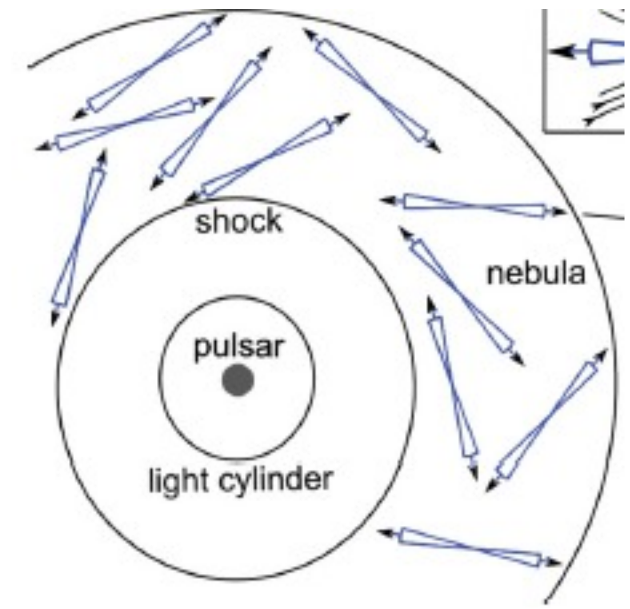


Deng et al. 2014 in preparation

Extreme Acceleration/Radiation in AGNs, GRBs, and PWNs

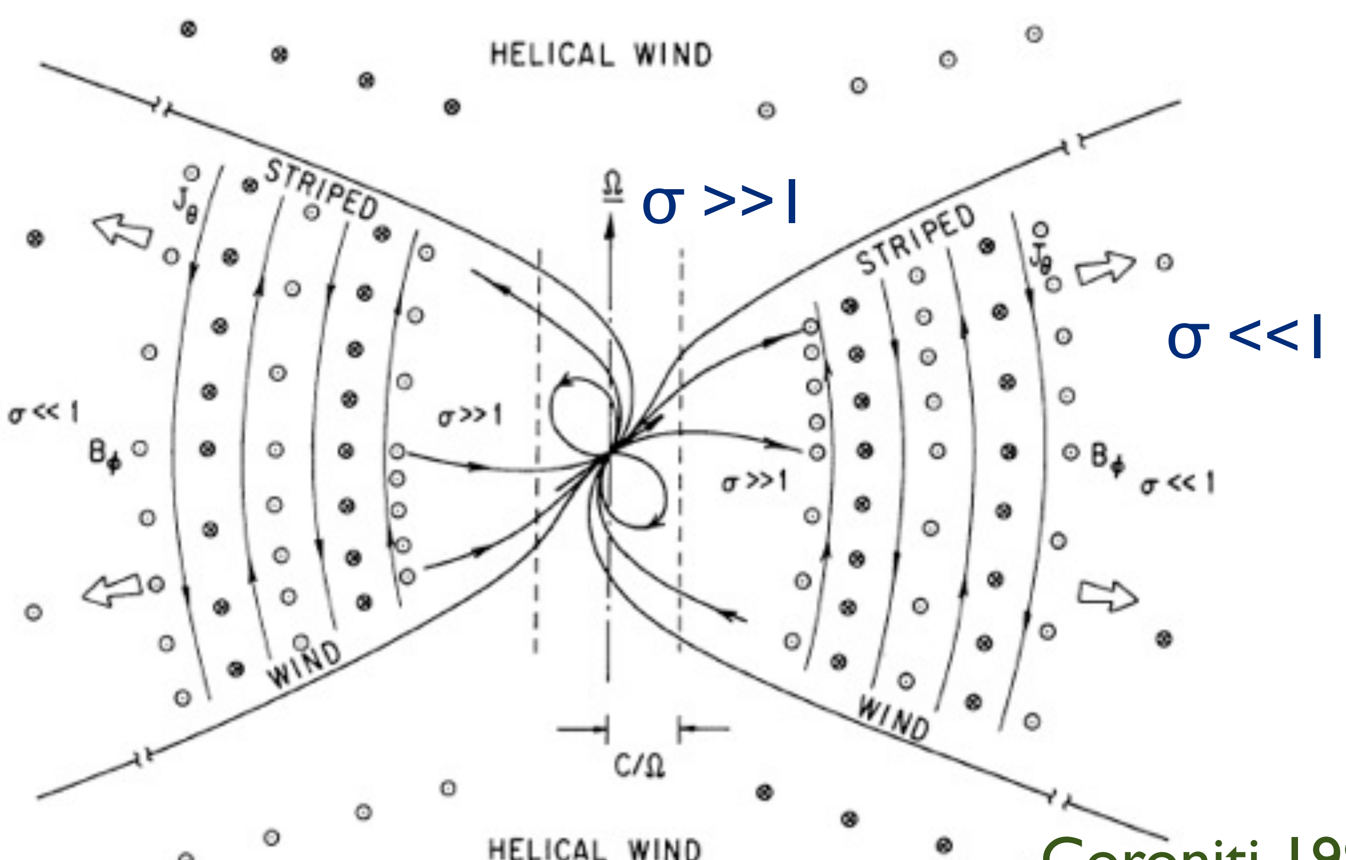
superflares: extreme particle acceleration





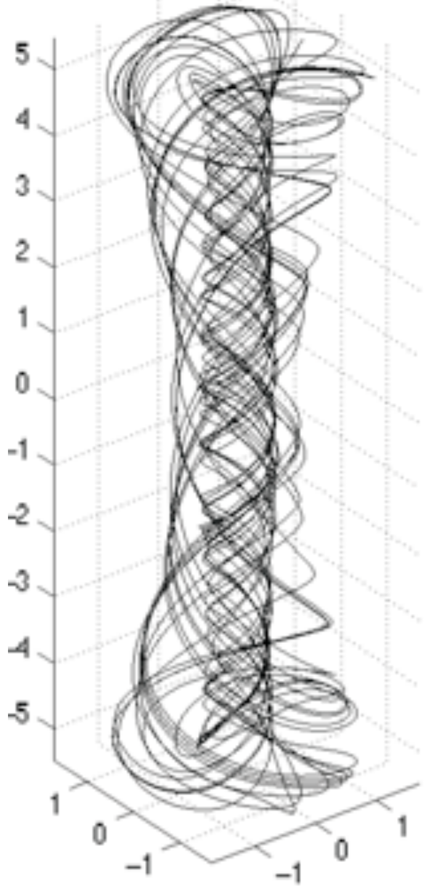
Clausen-Brown & Lyutikov

σ-problem: fast magnetic dissipation



Coroniti 1990

Porth et al. 2013

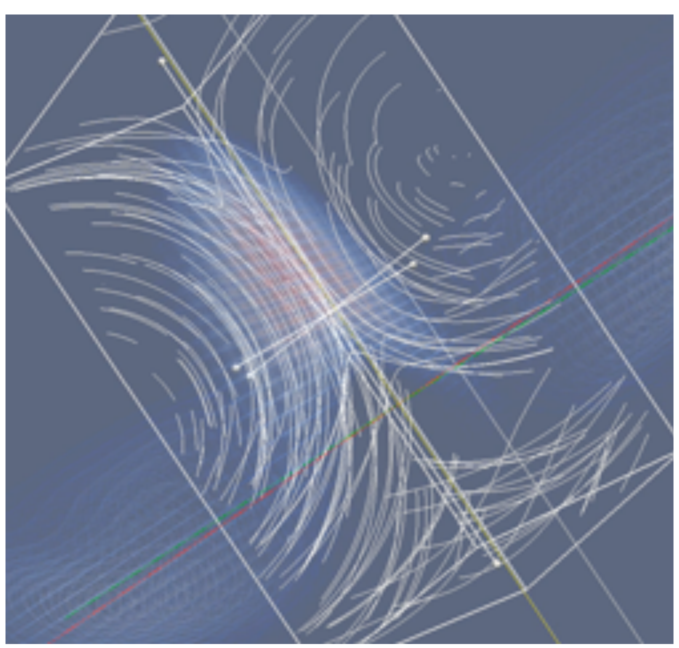


Large-scale field reversal

Lynden-Bell et al. 96

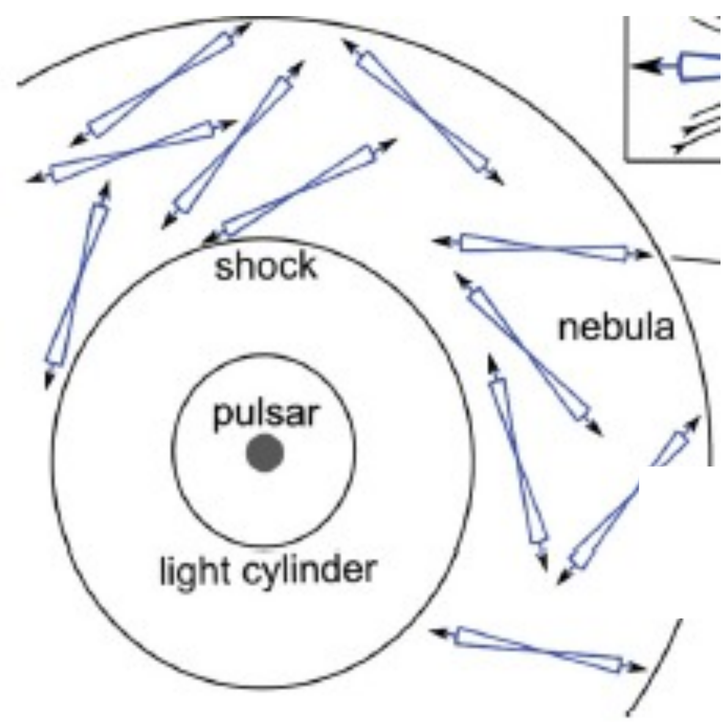
Li et al. 06

Porth et al. 2013



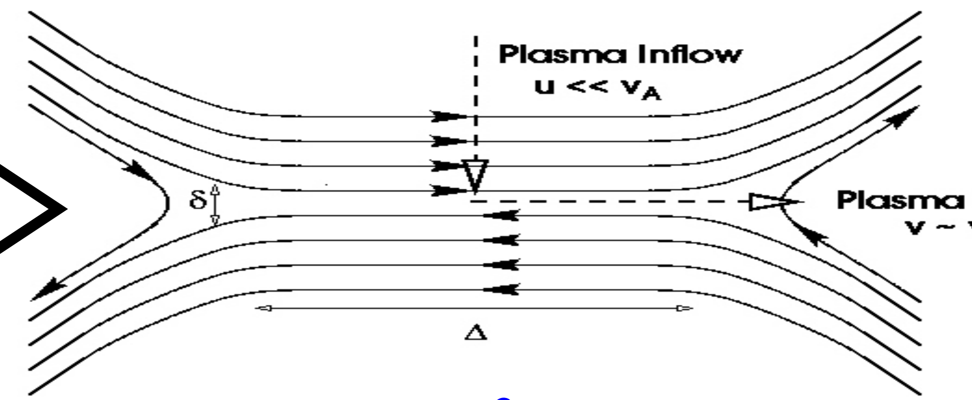
Blob collision

Deng et al. 2014 in preparation



Clausen-Brown & Lyutikov

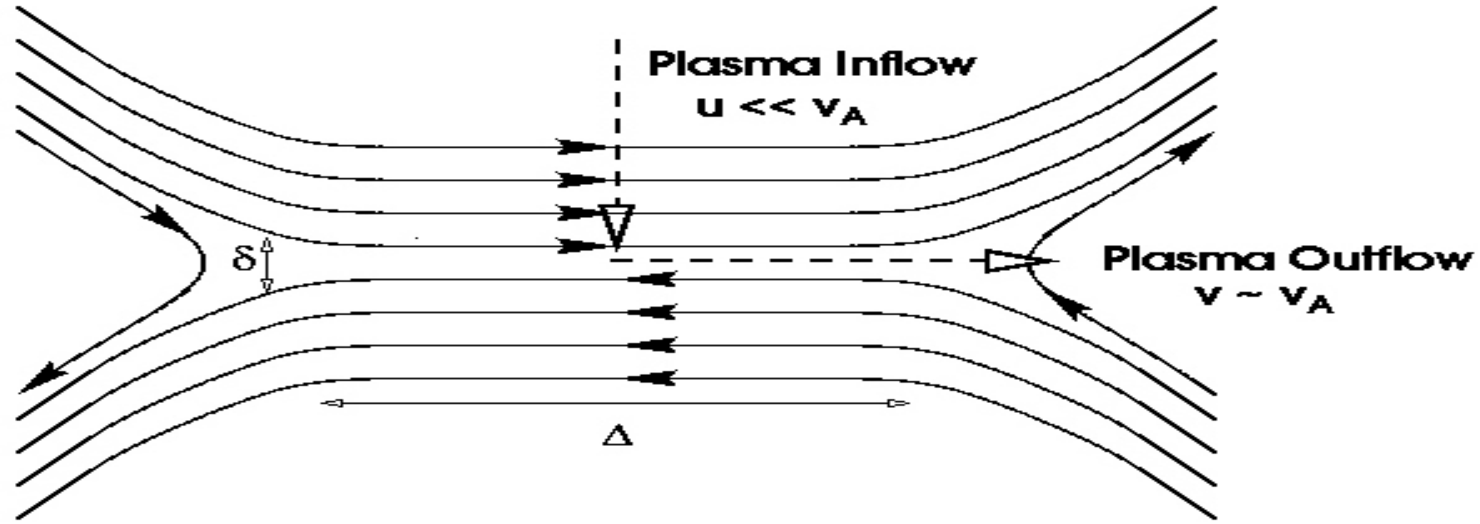
A general local geometry



$$\sigma = \frac{B^2}{4\pi nmc^2} >> 1$$

Look into details ...

Focusing on a local reconnection site with σ>>1

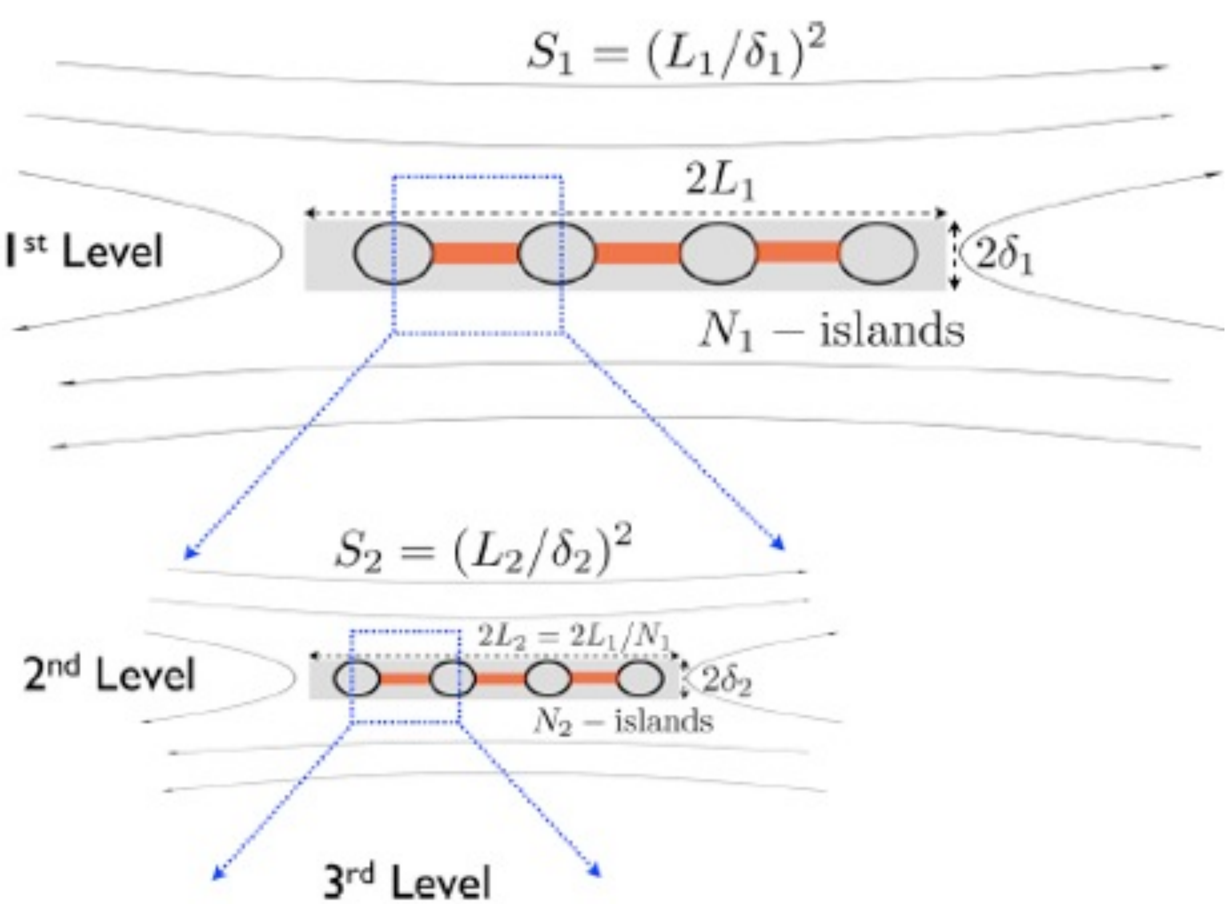


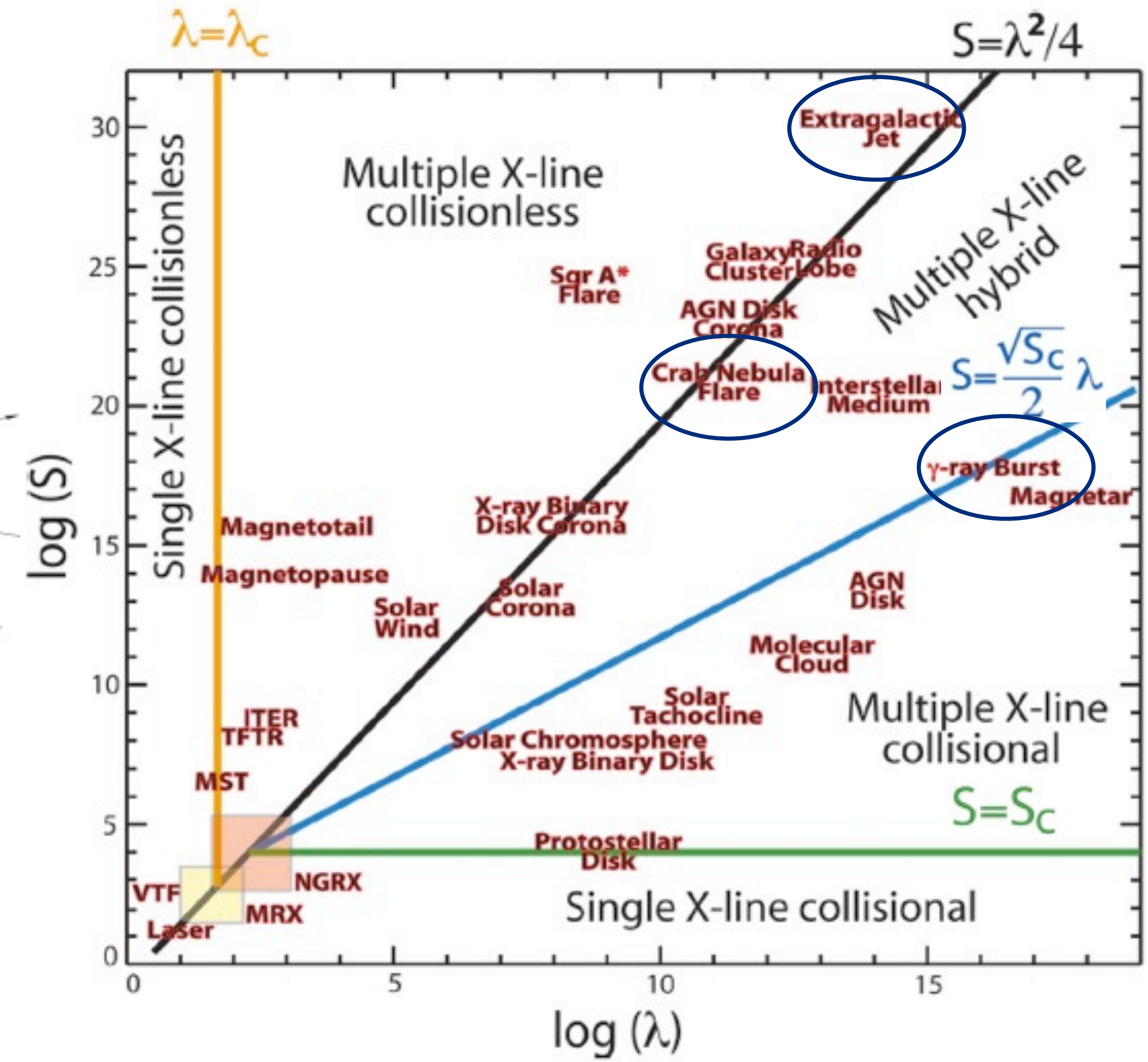
- Strong particle acceleration and formation of hard power laws $dN/d\gamma = \gamma^{-p}$, p~1.
- Acceleration mechanism: first-order relativistic Fermi process
- Power-law model and formation condition ($\tau_{acc} < \tau_{inj}$).
- Properties of relativistic magnetic reconnection:
  Relativistic inflow and outflow
  Reconnection rate is enhanced because of relativistic effect.

Guo, F. et al. PRL in press
Arxiv: 1405:4040

Phase diagram for magnetic reconnection

hierarchy of interacting
current sheets and islands





Ji & Daughton 2011

Particle-in-cell Kinetic Simulations

Relativistic particle motions

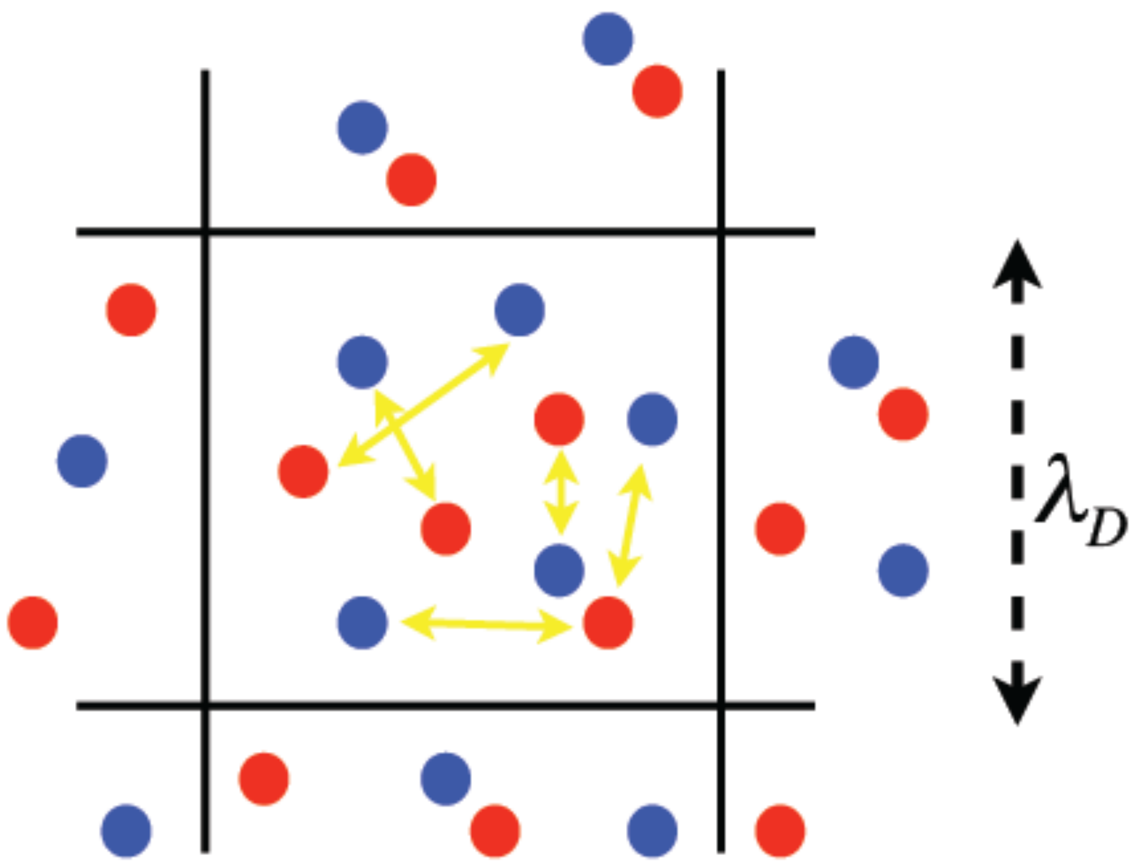
+

Maxwell equations

$$\frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \frac{\partial f_s}{\partial \mathbf{x}} + \frac{q_s}{m_s}\left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right) \cdot \frac{\partial f_s}{\partial \mathbf{p}} = 0$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \cdot \mathbf{E} = 4\pi\rho \qquad \nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$



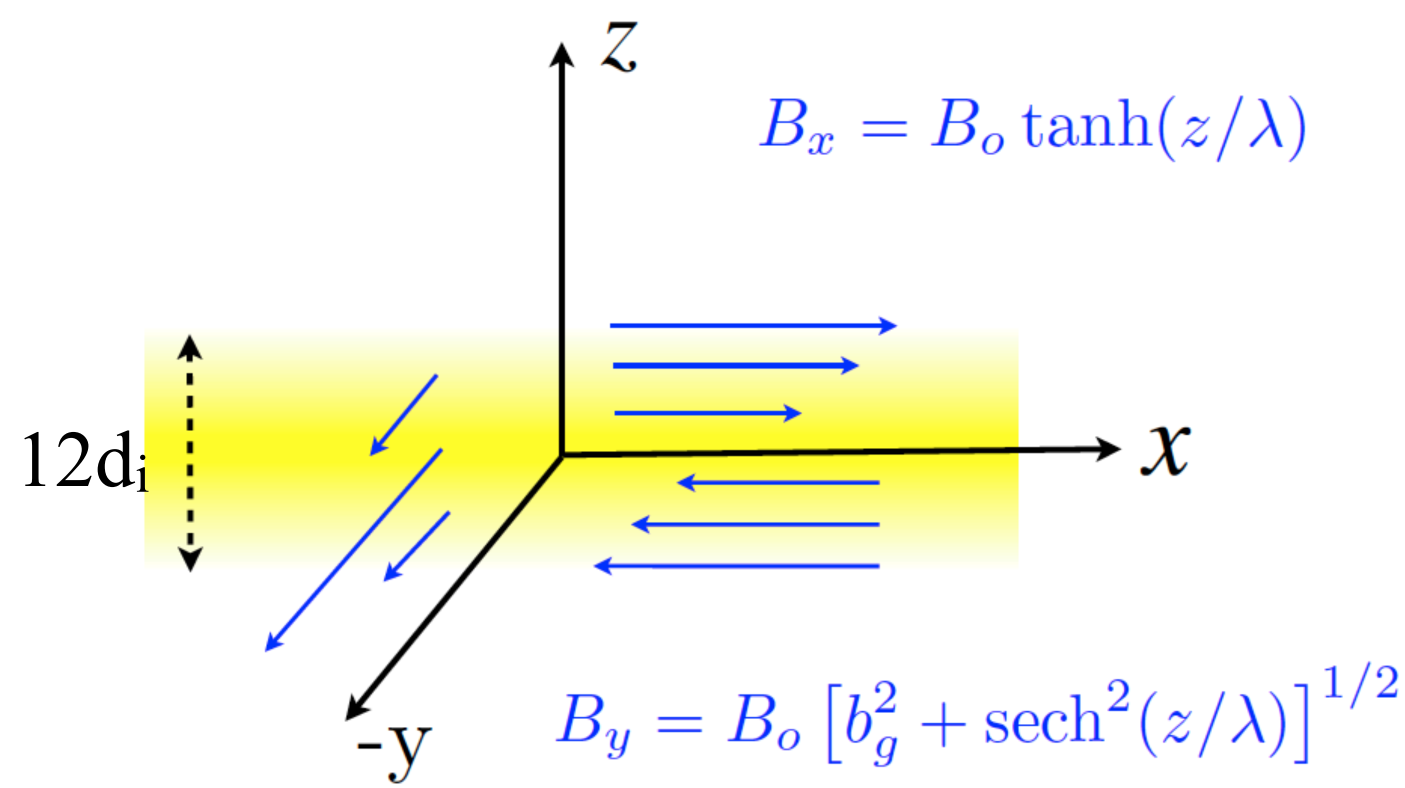
✔ First-principle kinetic description

✘ Expensive for large scales

Use LANL's VPIC on supercomputers (Blue Waters, Titan, etc.)

Initial Setup & Parameters

• Initial configuration:
Force-free current sheet
(e.g., Che et al. 2011; Liu et al. 2013)



• Magnetic energy dominant initially $E_B >> E_k$

$$\sigma = \frac{B_0^2}{4\pi n_0 m_e c^2} = \left(\frac{\omega_{ce0}}{\omega_{pe0}}\right)^2 >> 1$$

• Pair plasma ($m_i/m_e = 1$)
initially, $E_{the} = E_{thi} = 0.36mc^2$

2D: σ = 1-1600

$$L_x \times L_z = 300 d_i \times 194 d_i \quad 600 d_i \times 388 d_i$$
$$1200 d_i \times 776 d_i$$

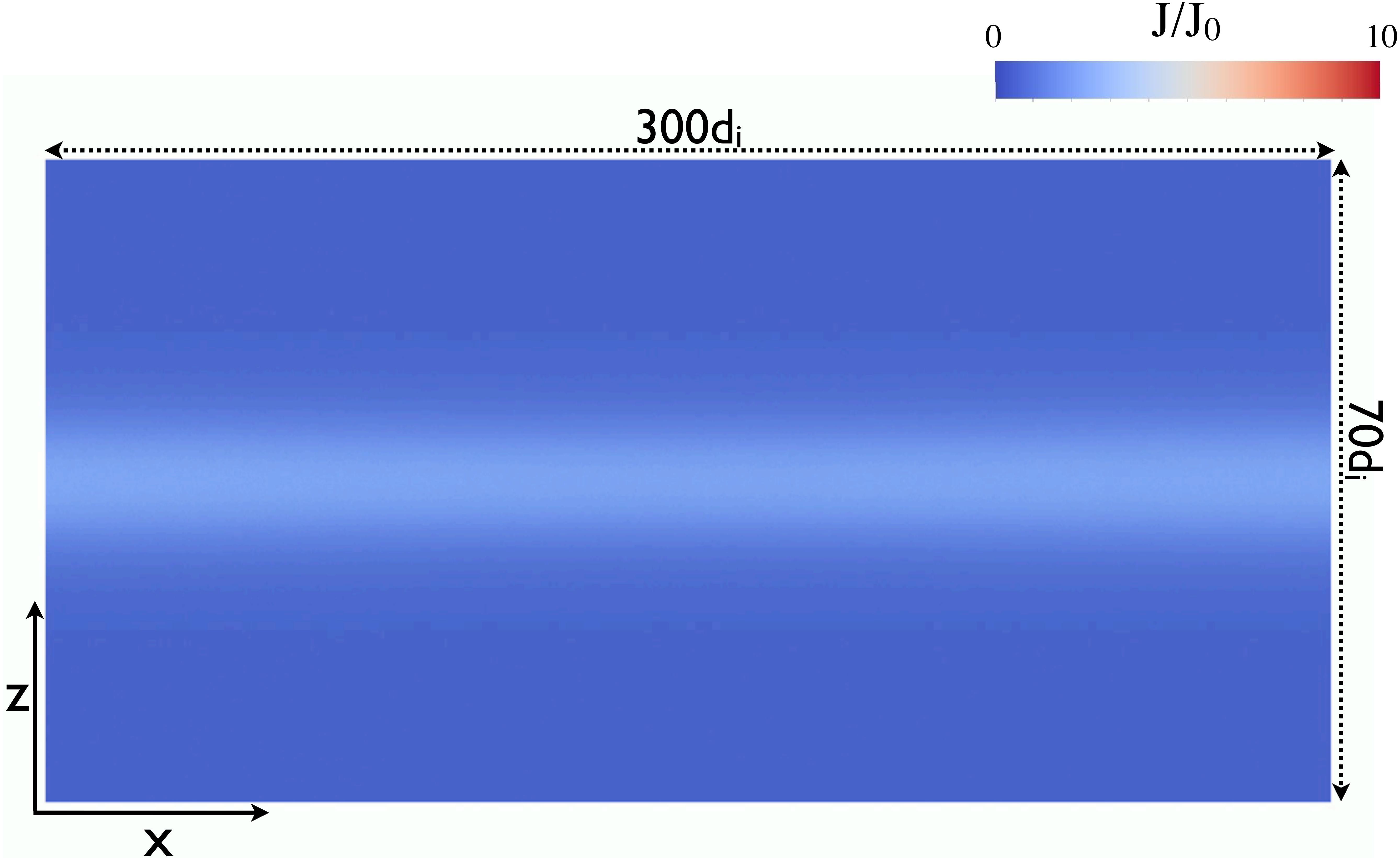
3D: σ up to 100

$$L_x \times L_z \times L_y = 300 d_i \times 194 d_i \times 300 d_i$$

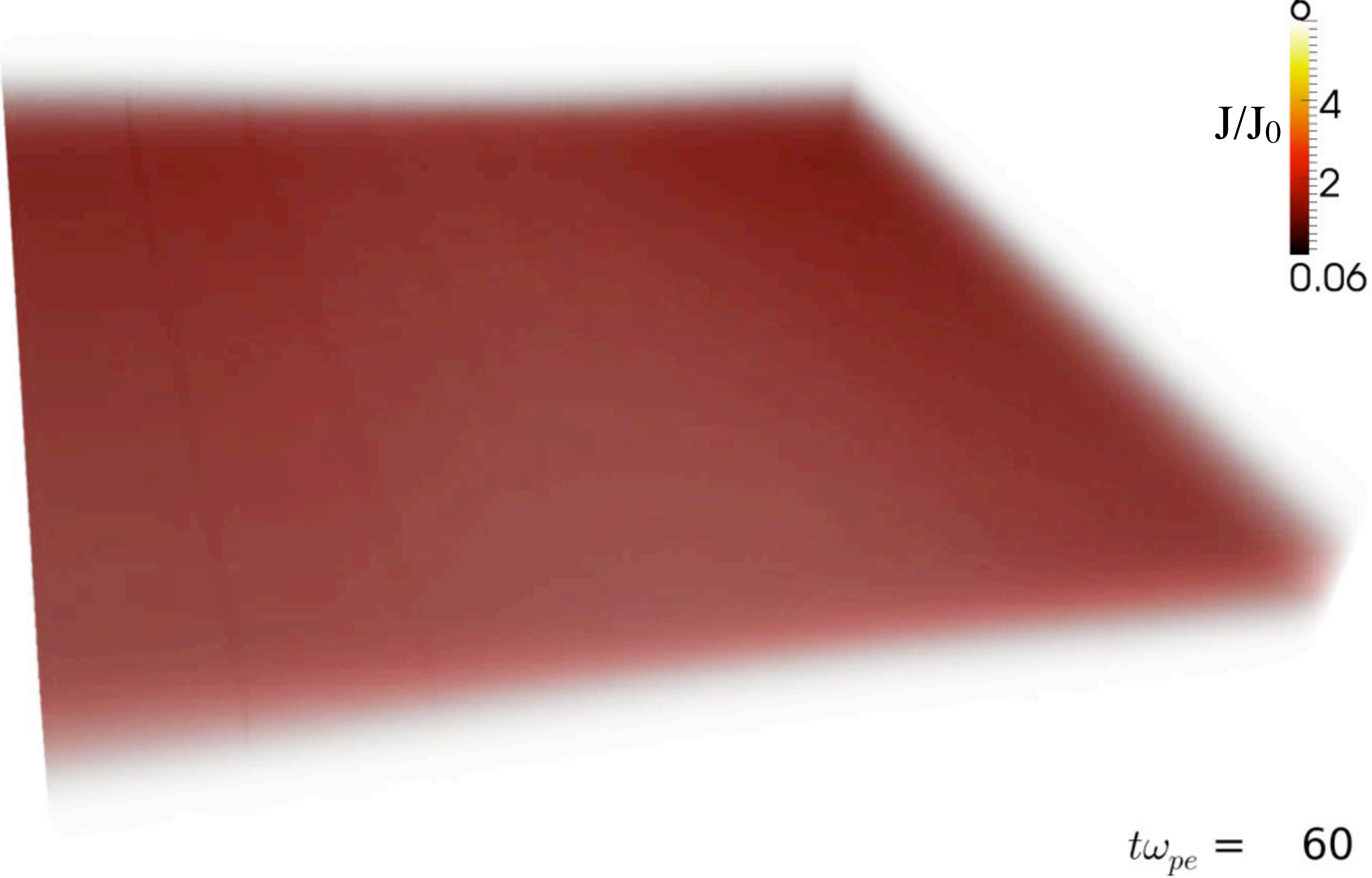
Boundaries for fields: x - periodic
z - conducting
y - periodic (3D)
Boundaries for particles: x - periodic
z - reflection
y - periodic (3D)
No guide field: bg = 0
Initial perturbation (GEM challenge)

~1.4 trillion particles and 2048^3 grids on Blue Waters

2D current density (σ=100) $\omega_{pe}t$=0 - 700

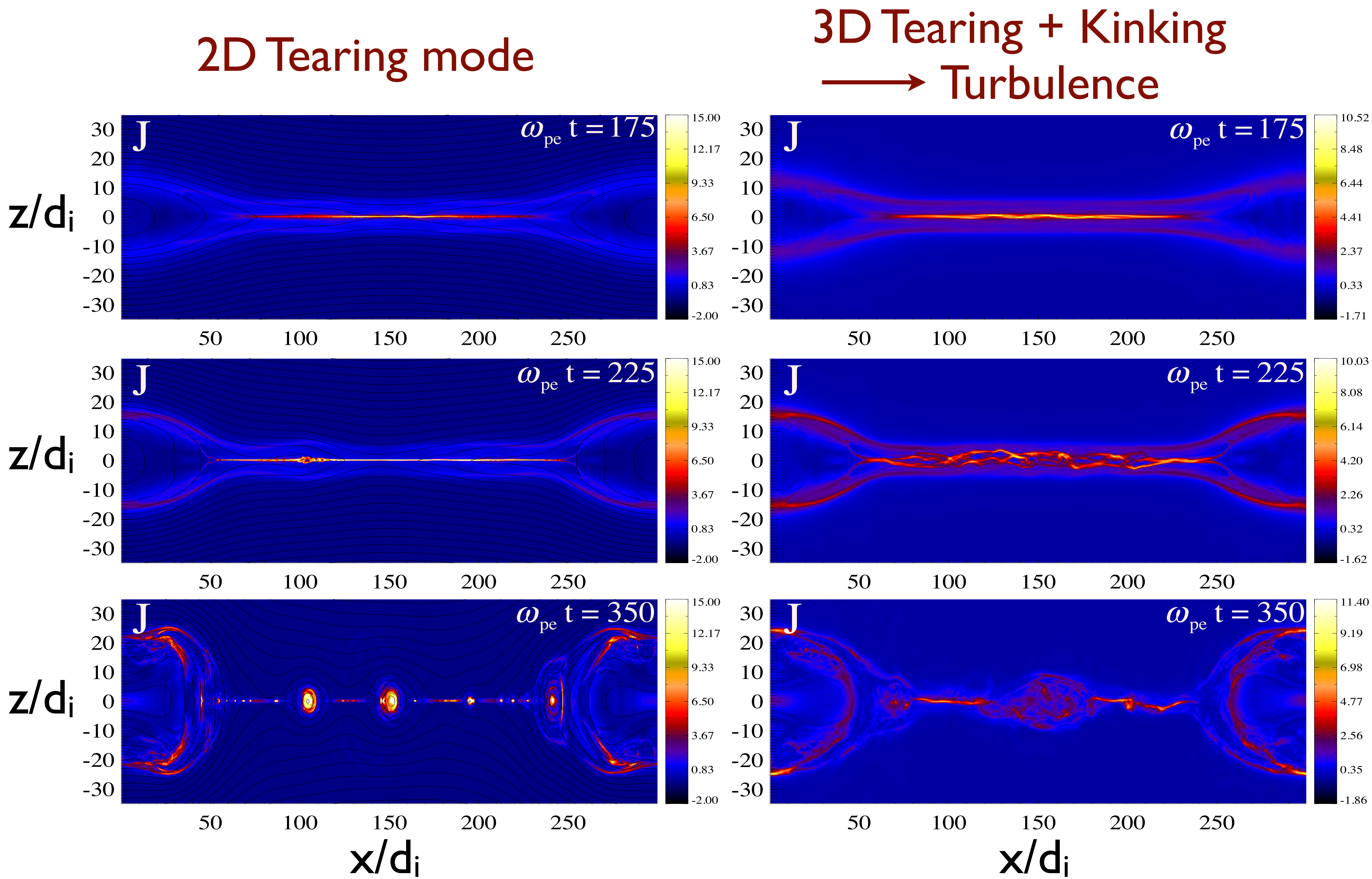


Guo et al. 2014 PRL, in press

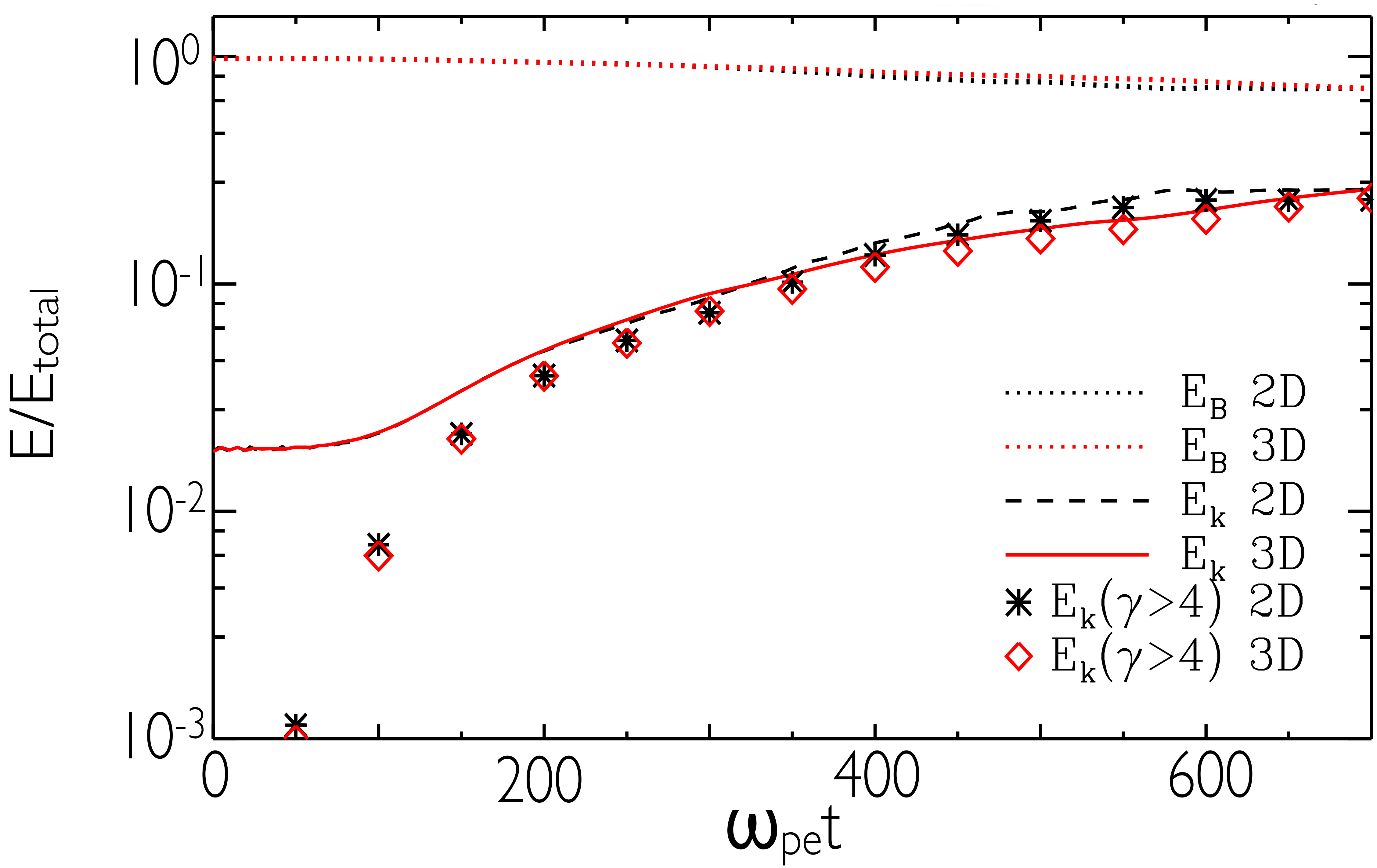


6
4
2
0.06
J/J$_0$
$t\omega_{pe}$ = 60

Current-density structure in 2D and 3D (σ=100)

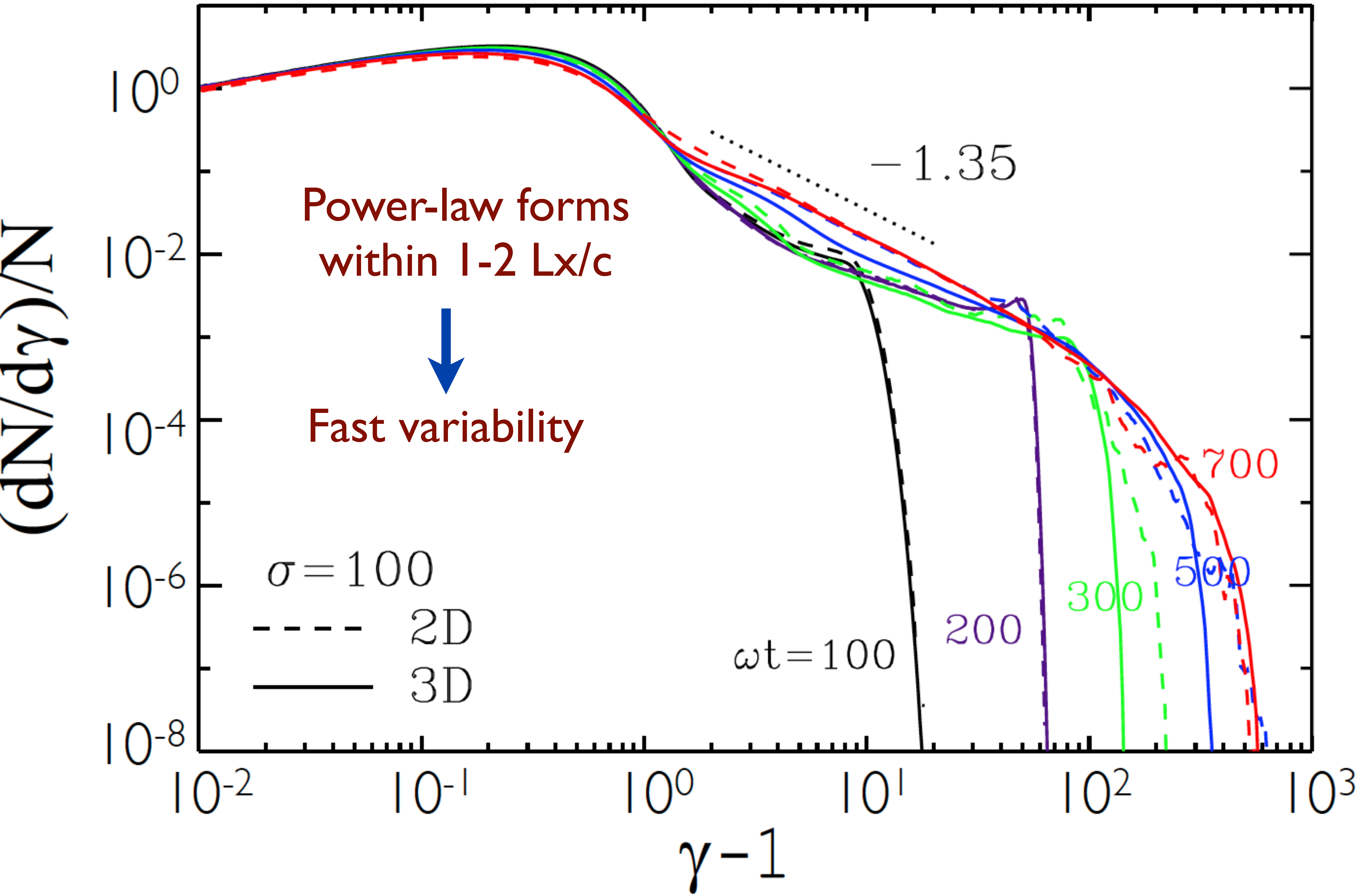


Energy evolution from 2D and 3D PIC simulations

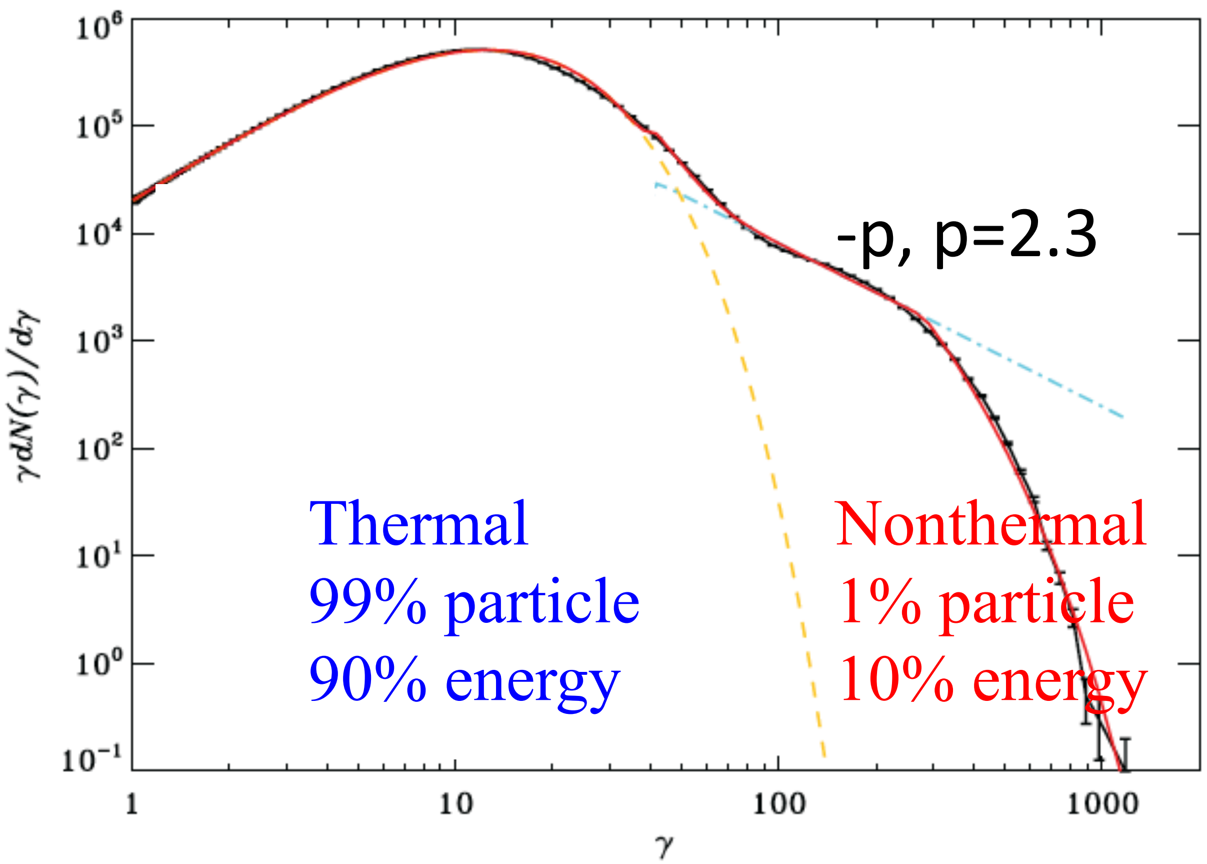


Magnetic energy is rapidly converted into relativistic plasmas.
3D & 2D results are surprisingly similar.

Energy spectra from 2D and 3D PIC simulations

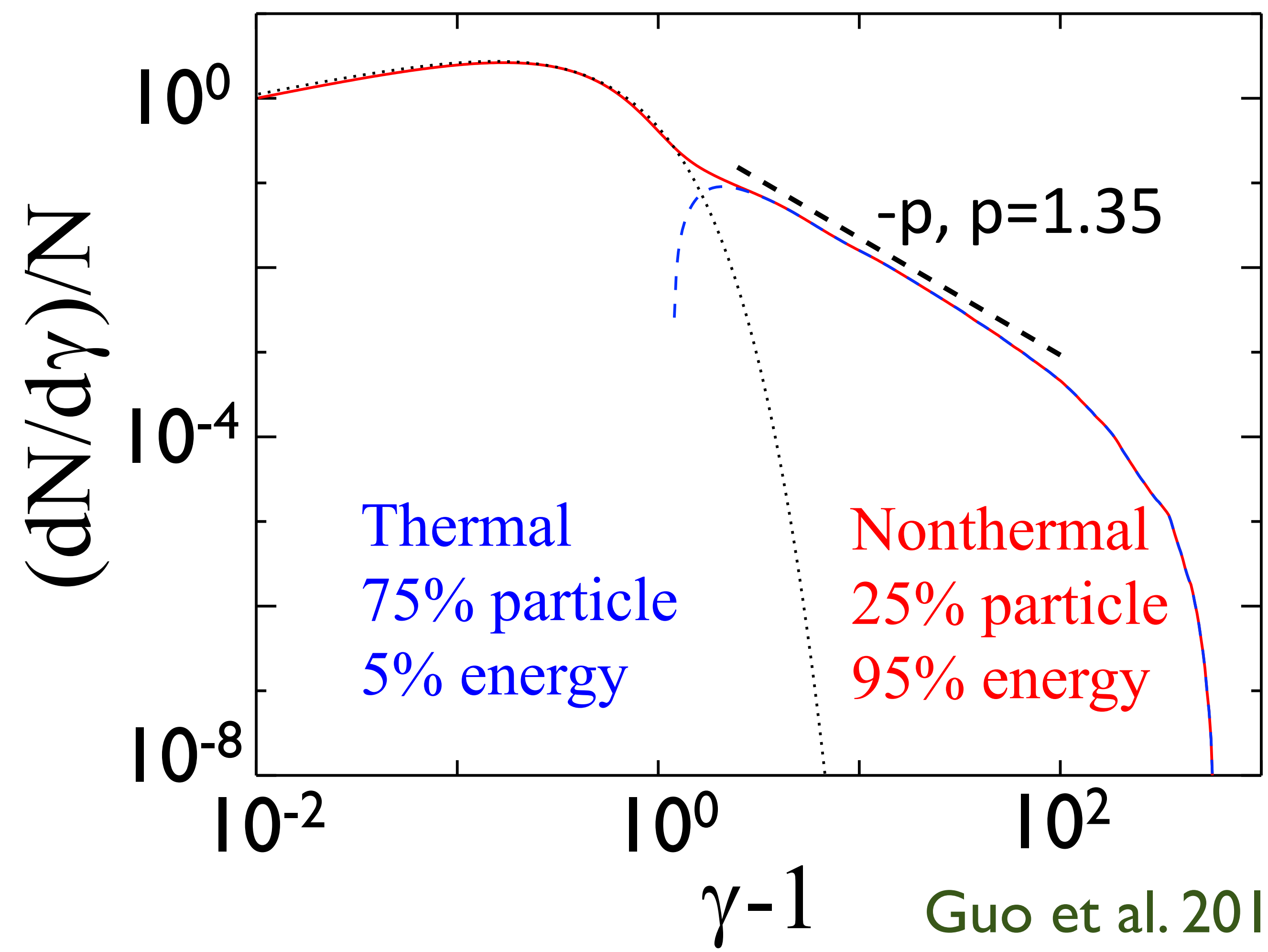


Shock vs Reconnection



Spitkovsky 2008

Shock heating dominant

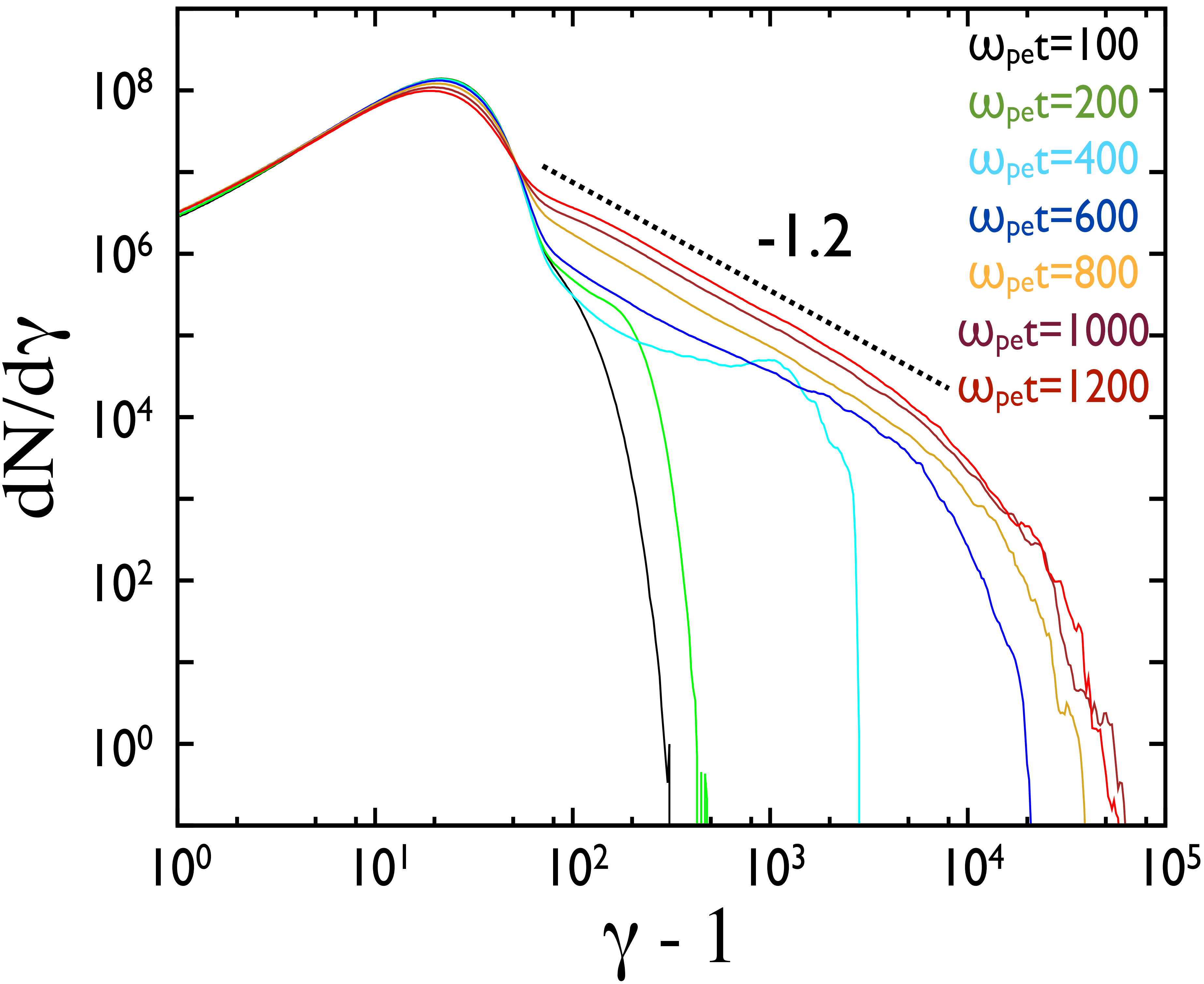


Guo et al. 2014
PRL in press

Nonthermal Acceleration dominant

Thermal distribution contains most of kinetic energy

The accelerated power-law tail contains most of kinetic energy.



Spectral index p ~ 1

Fast variability ~ Lx/c

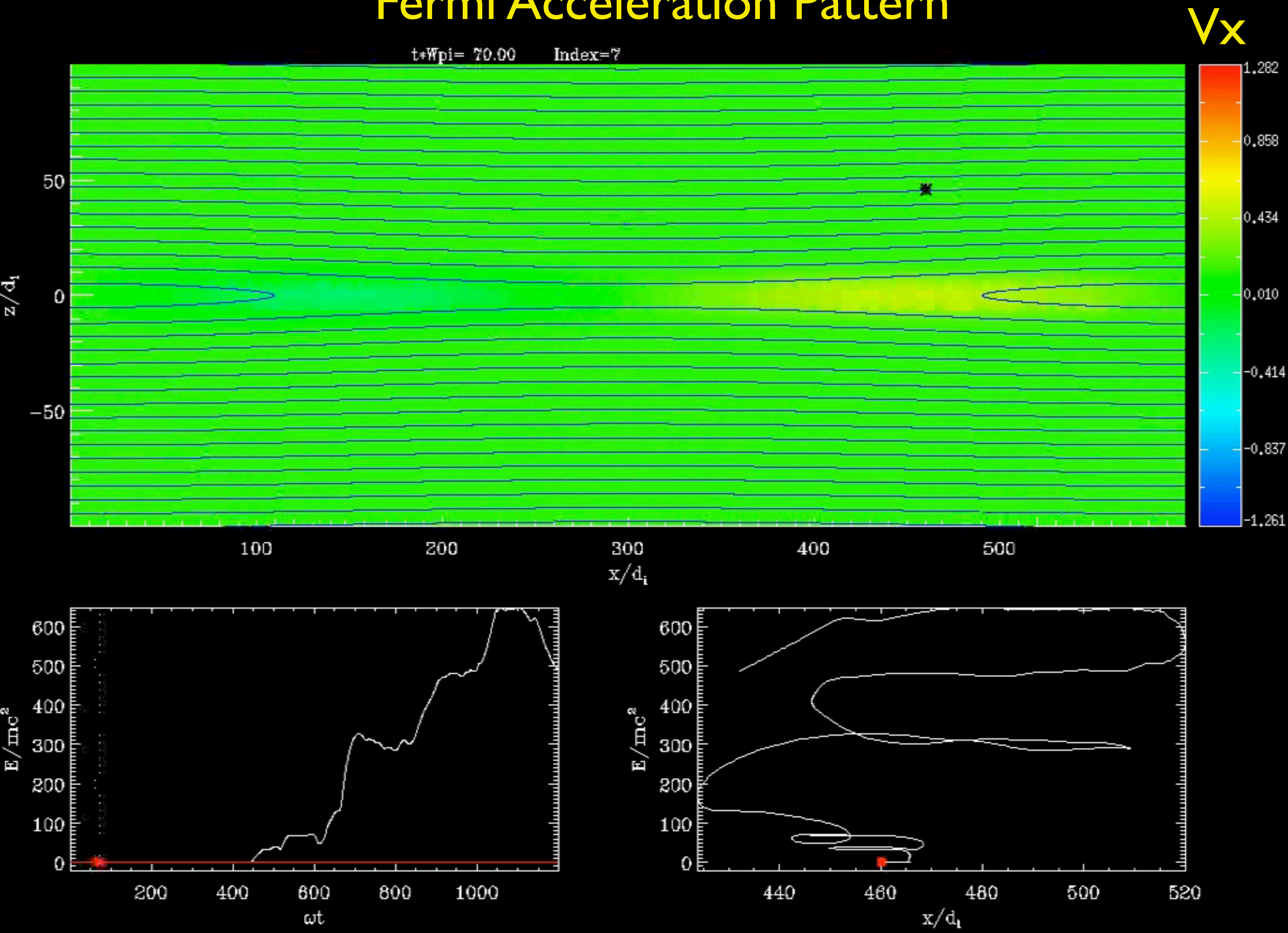
Power-law range

$\gamma_2 \sim \sigma$

$\varepsilon_{\max} \sim \int qE_{rec} c\, dt$

E_{rec} up to ~ $0.3B_0$ for σ>>1

Fermi Acceleration Pattern



1st order Fermi mechanism

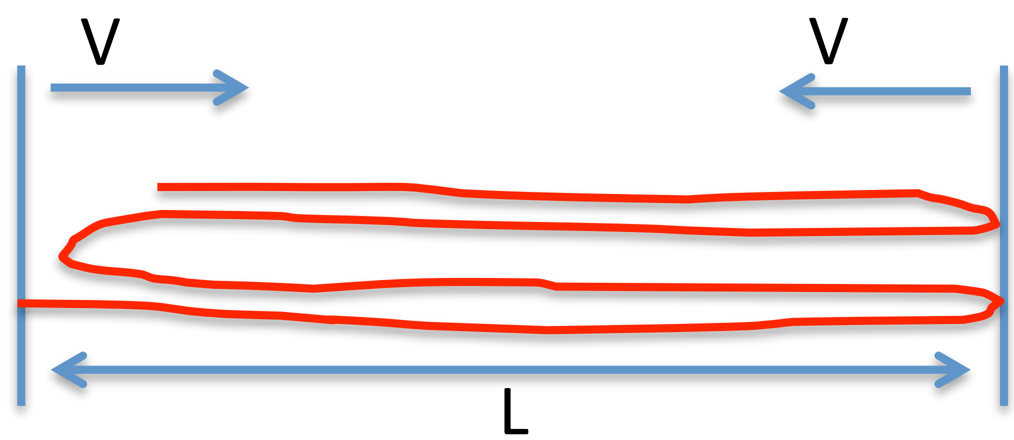
- Acceleration by "collision" in between moving magnetic clouds (Fermi 1949)

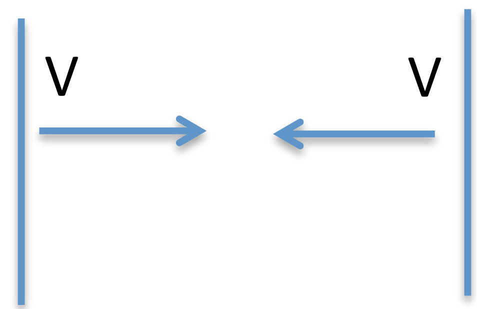
$$\Delta E = \gamma_V^2 E(1 + 2Vv_x / c^2 + (V/c)^2)$$

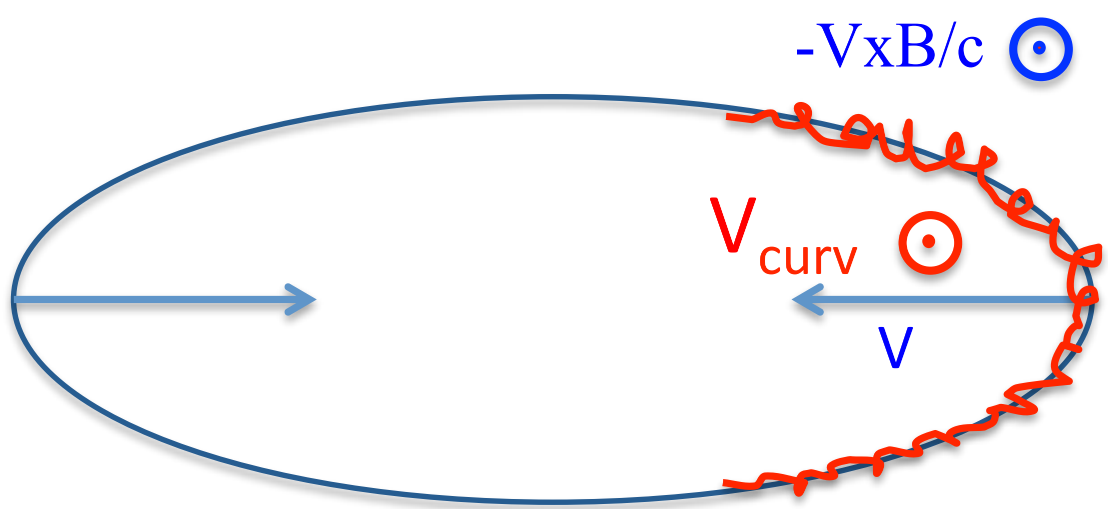
$$\Delta t = L / v_x$$

- In collisionless plasma $\mathrm{E} \sim -\mathrm{VxB/c}$

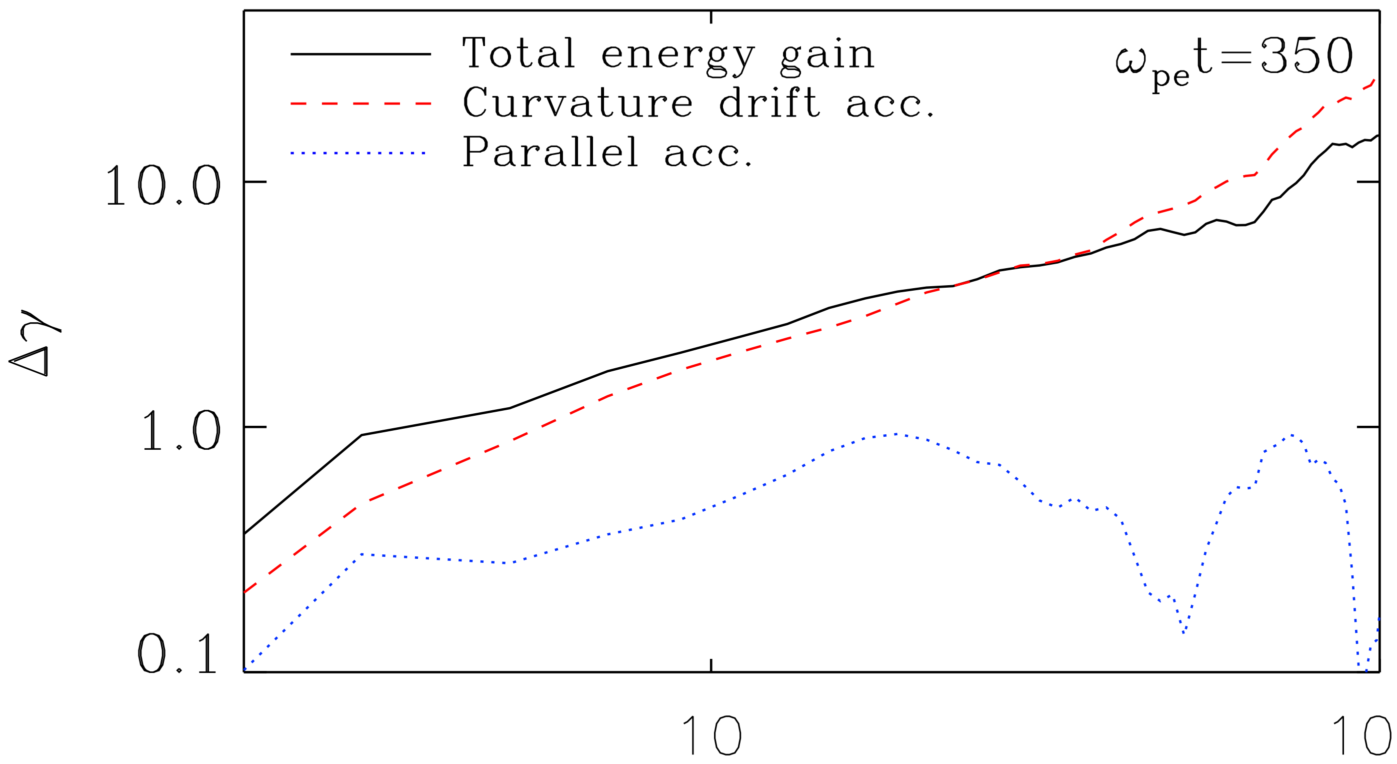
- In the case of reconnection generated plasmoids/flux tubes, the Fermi process is accomplished by curvature drift motion in plasmoids along the motional electric field induced by plasma flows.



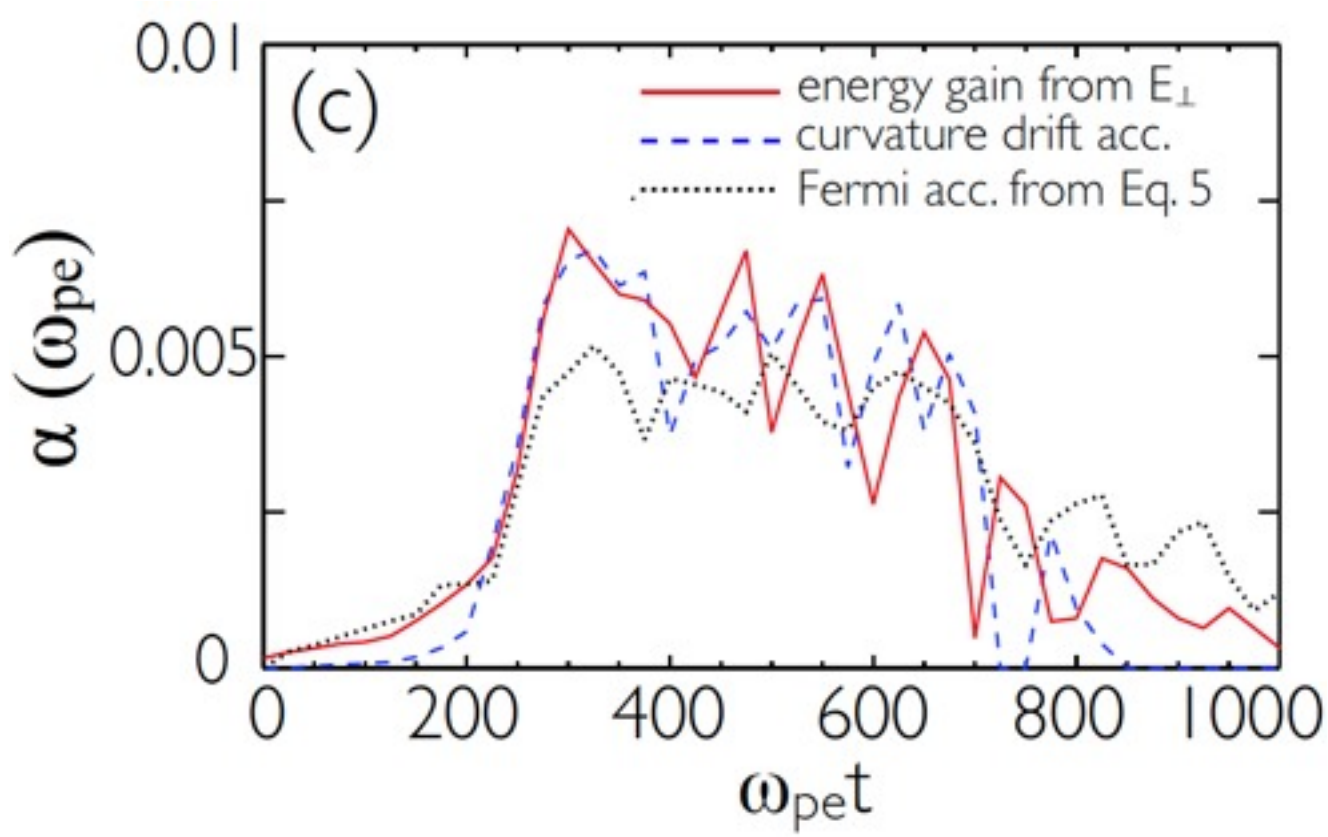




Type-B Fermi process (Fermi 1949)
Drake et al. 2006, 2010; Birn et al. 2012
Guo et al. 2014



The acceleration is dominated by curvature drift motion in reconnecting electric field

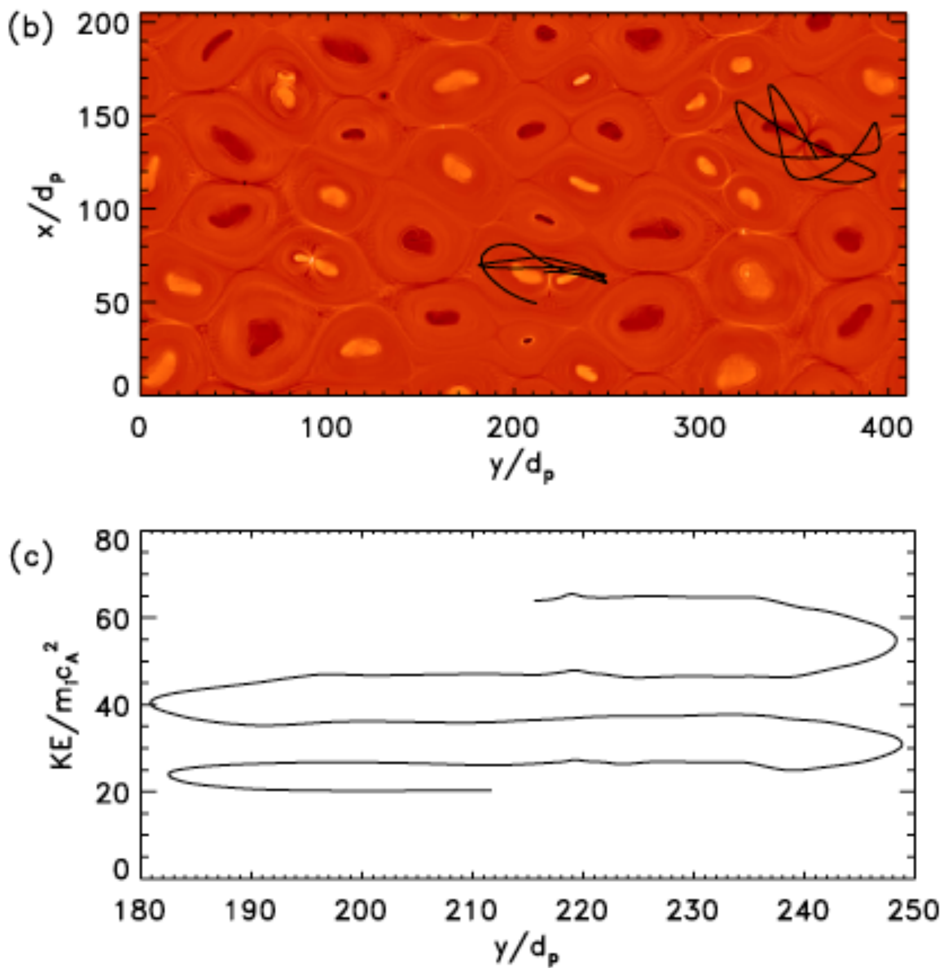


Fermi acceleration is facilitated by curvature drift motion in electric field induced by relativistic flow

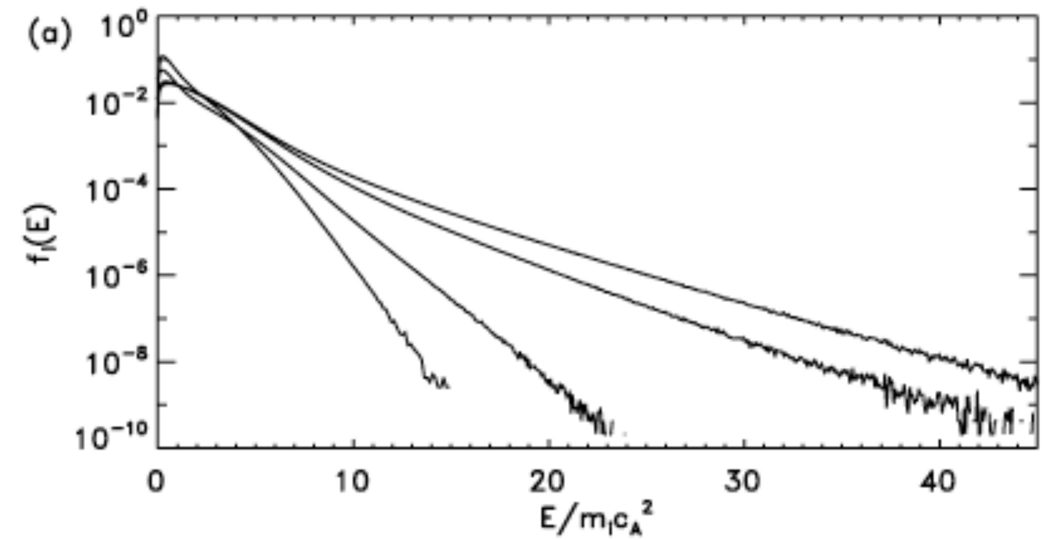
$$\Delta E = \gamma_V^2 E(1 + 2Vv_x / c^2 + (V / c)^2)$$

$$\Delta t = L / v_x$$

Why power law?

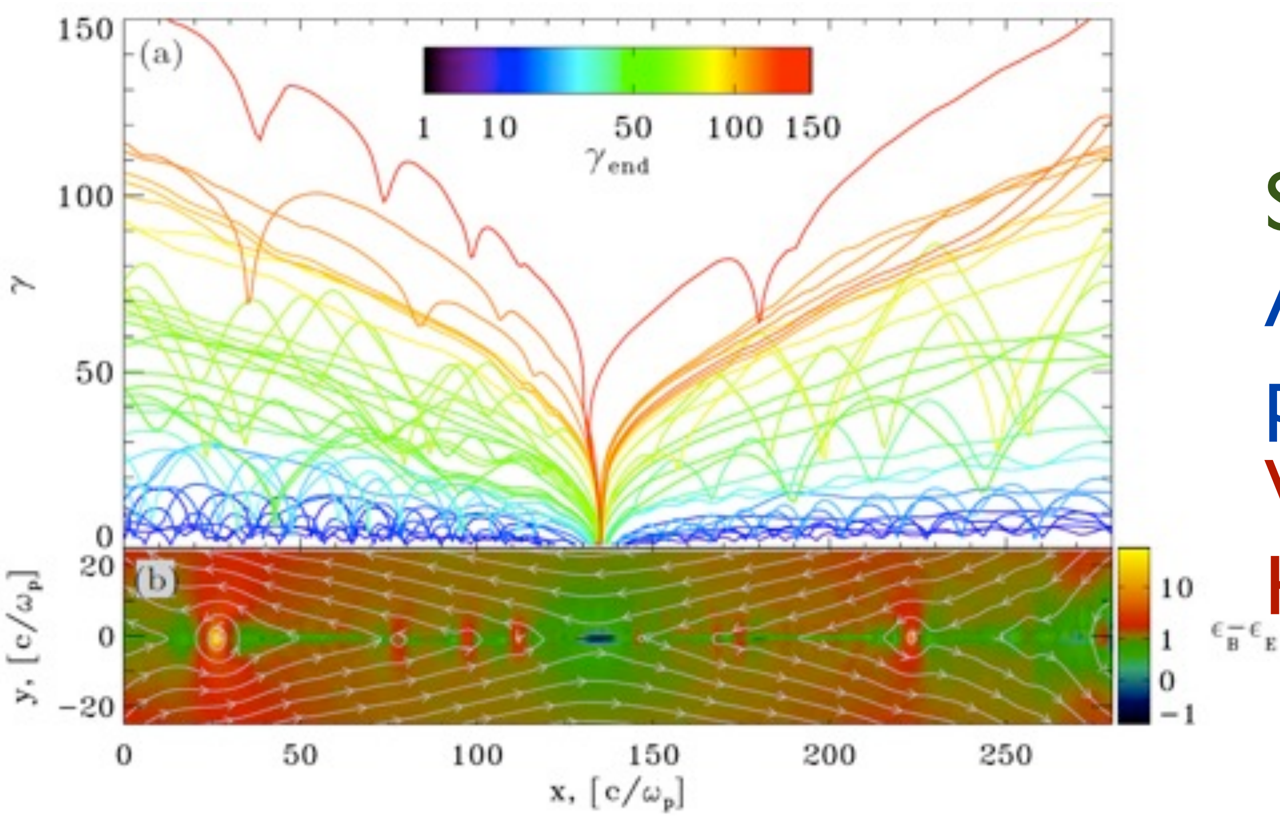


Drake et al. (06, 10, 13)



No power laws in a close system?

Really need loss term?



Sironi & Spitkovsky 14; Melazani et al. 14

A part of the particles in the system show power-law distribution.

What is the acceleration mechanism?

How does the power law form?

Formation of power laws (Fermi 1949)

$$\cancel{\frac{\partial f}{\partial t}} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = -\frac{f}{\tau_{esc}}$$

$$\frac{\partial}{\partial \varepsilon}(\alpha \varepsilon f) = -\frac{f}{\tau_{esc}} \qquad f \propto \varepsilon^{-(1+1/\alpha\tau_{esc})}$$

A closed system

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = 0$$

$$f_0 \;=\; \frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}\,\exp(-\varepsilon)$$

$\mathcal{E} = mc^2(\boldsymbol{\gamma}-1)/\mathrm{kT}$

Assuming $\alpha = \partial\mathcal{E}/\partial t/E$, solution after time t:

$$\frac{df}{dt} + \alpha f = 0$$

$$f = \frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}e^{-3\alpha t/2}exp(-\varepsilon e^{-\alpha t})$$

Just T → $Te^{\alpha t}$

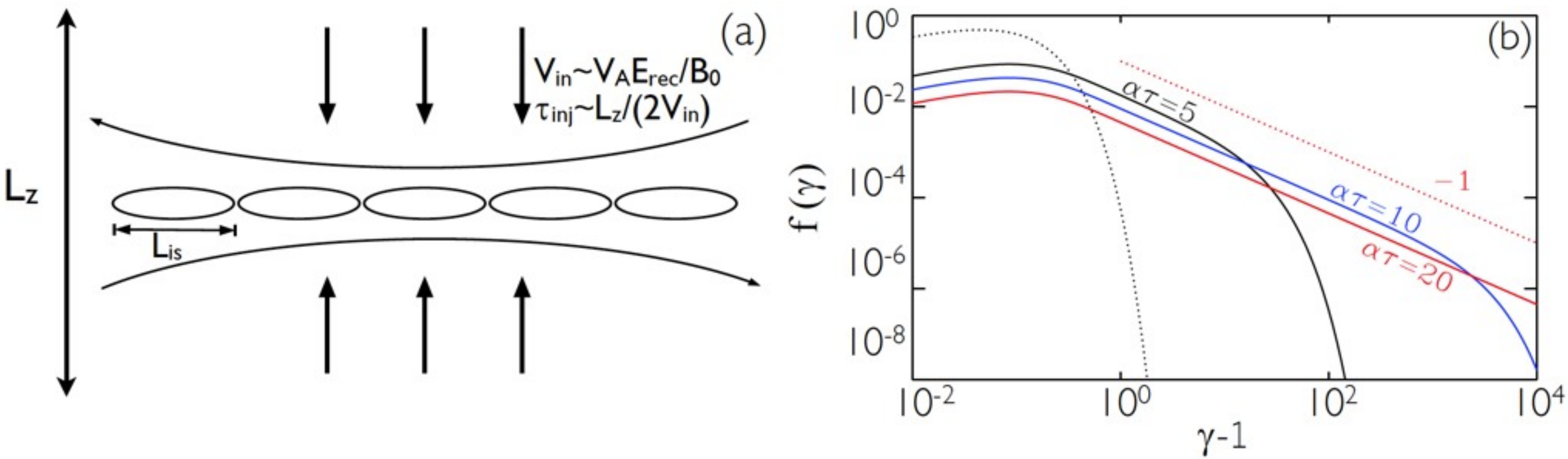
Consider escape

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = -\frac{f}{\tau_{esc}}$$

$$\frac{df}{dt} + \alpha f = -\frac{f}{\tau_{esc}}$$

Have the same solution Just $T \rightarrow Te^{(\alpha + 1/\tau_{esc})t}$

Power-law formation

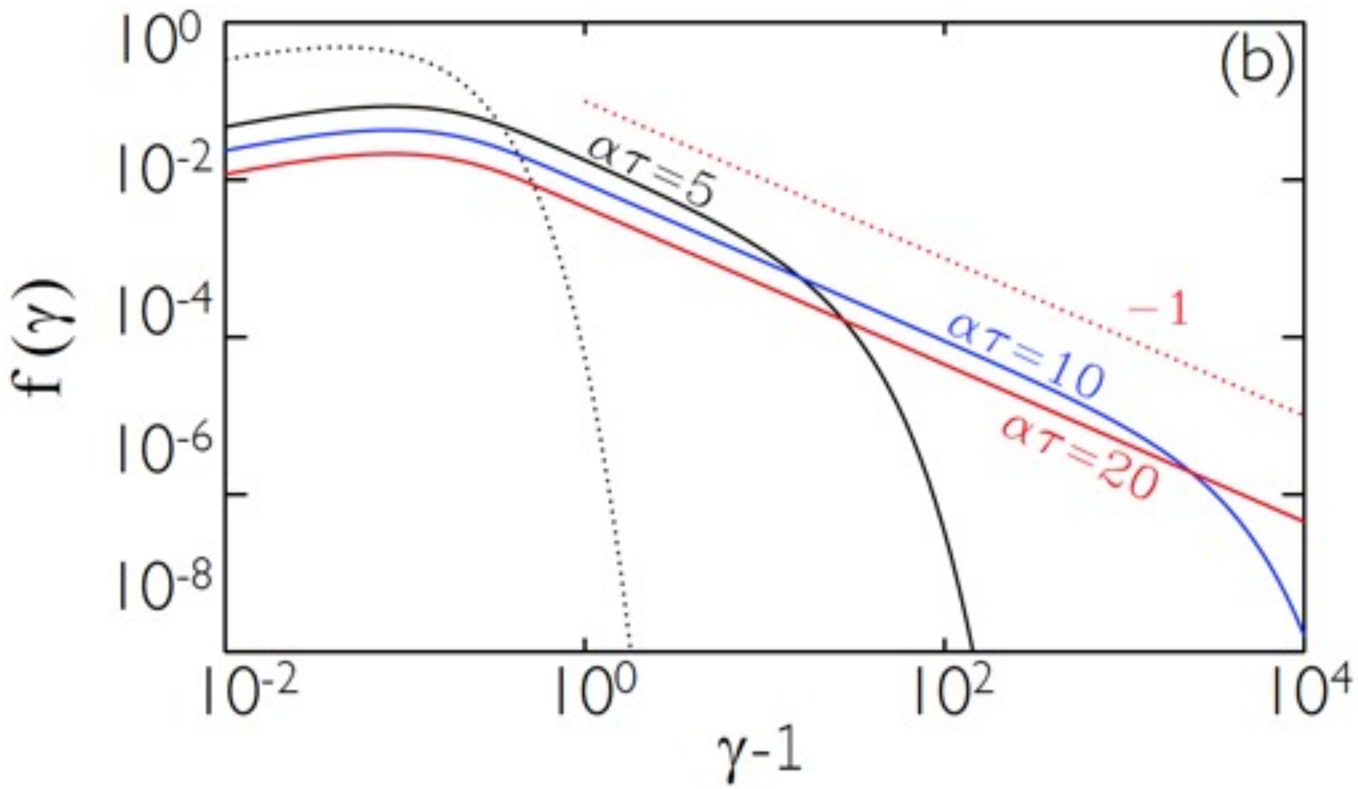


$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial E}(\dot{E} f) = \frac{f_0}{\tau_{inj}} - \frac{f}{\tau_{esc}} \qquad f \propto \varepsilon^{-(1+1/\alpha\tau_{esc})}$$

Two important ingredients: inflow (injection) + Fermi acceleration

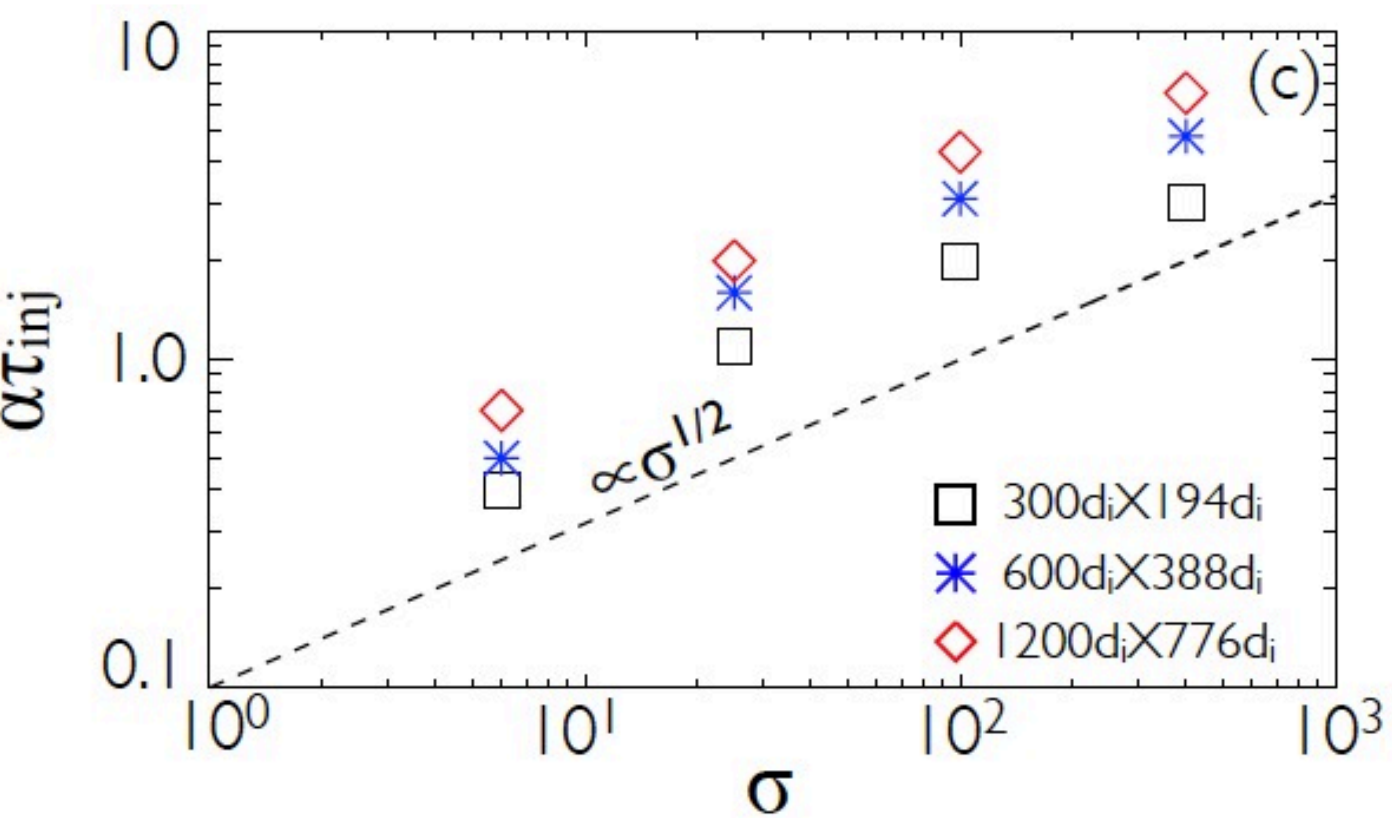
Periodic (closed) systems will give spectral index p=1.
Open boundary simulations show that energy spectra remain hard (~-1) for high-σ case, but softer for lower σ.

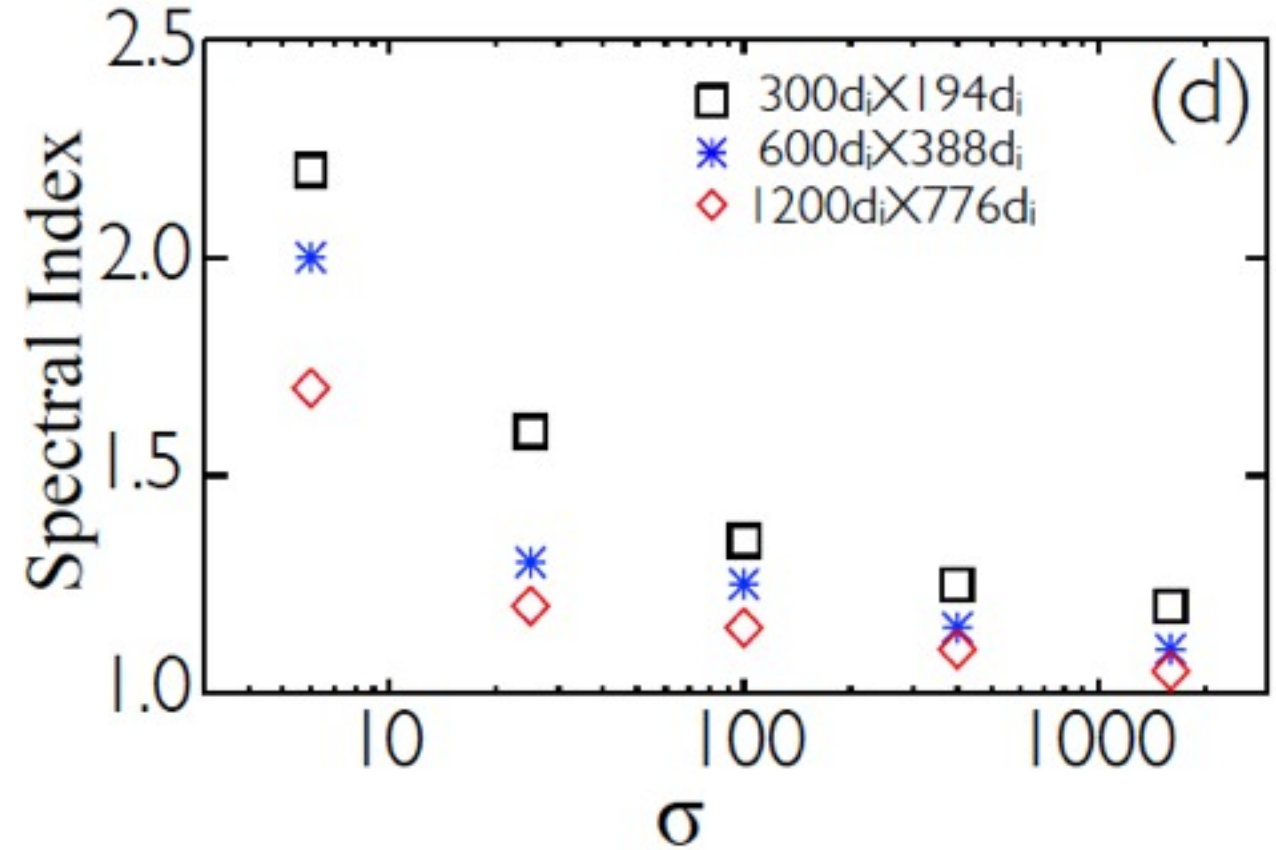
Power-law formation condition



$$\alpha\tau_{inj} > 1$$

This can easily be met in relativistic reconnection, even in kinetic scales!





Key results

- Fast reconnection and strong particle acceleration during magnetic reconnection in high-σ regime.
- Enhanced reconnection rate in relativistic regime. 2D and 3D give about the same rate.
- Efficient energy conversion and particle acceleration (nonthermal dominant)
- Dominant acceleration mechanism: first-order Fermi acceleration. 3D results are remarkably similar to 2D.
- Formation of power laws: requires both Fermi acceleration and continuous inflow. Power-law formation condition: $\alpha\tau_{inj}>1$.

Apply to high-energy astrophysics:

- Efficient energy conversion and strong particle acceleration (brighten the system in high-energy wavelengths)
- Hard power laws (close to "-1") in high-σ regime
- Fast power-law formation (fast variability)
- Relativistic inflow/outflow.

Magnetic Reconnection Rate: Determine E_{rec}

Reconnection rate is enhanced
in relativistic reconnection (Blackman & Field 94, Lyutikov & Uzdensky 03)

Stay nonrelativistic rate (Lyubarsky 05)

This study:
The rate is enhanced due to relativistic effect (Liu et al. 14 to be submitted)
2D and 3D simulations give the same rate. (Guo et al. PRL 14;
Guo et al.14 in preparation)

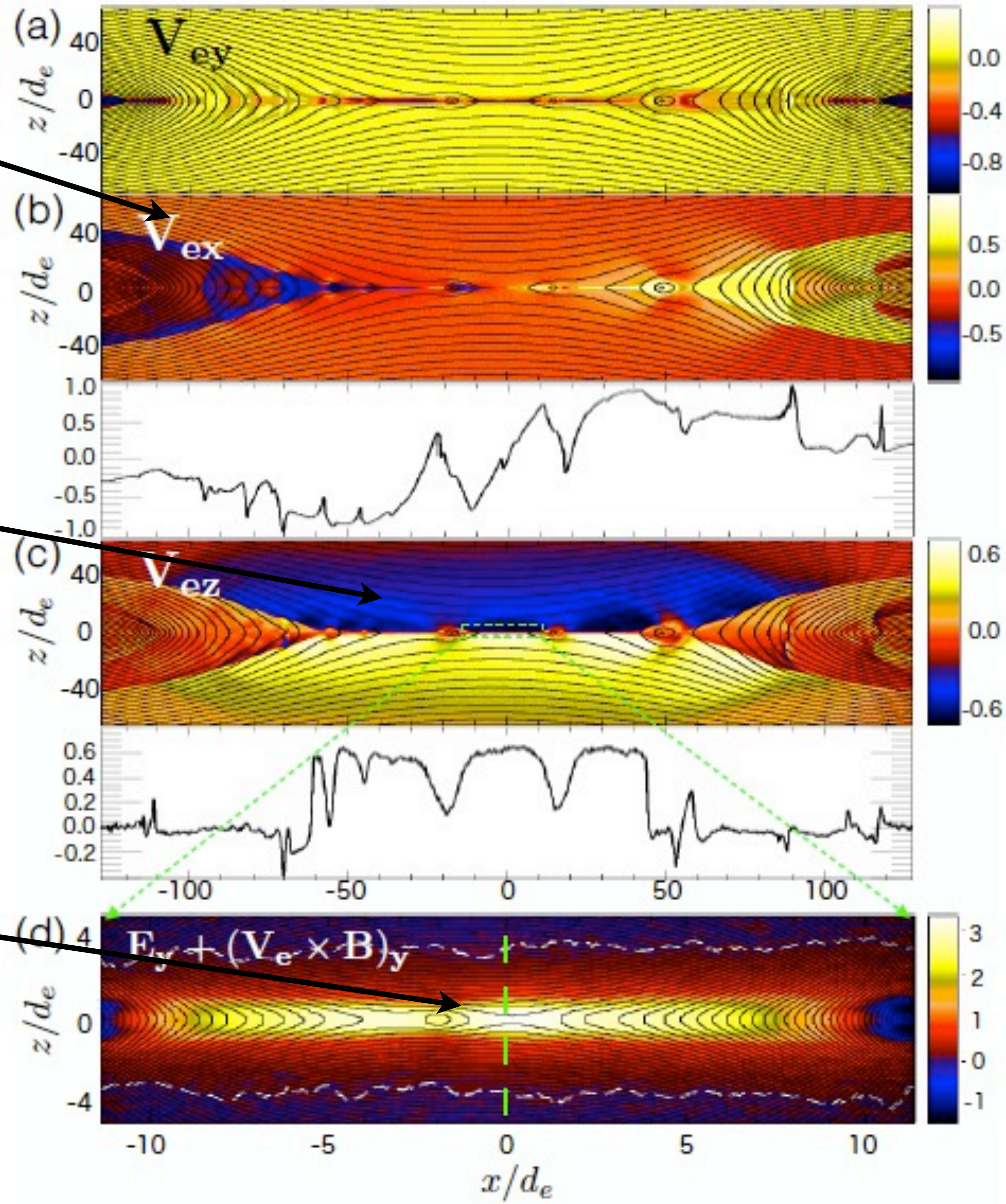
Global rate changes ~10 times: $E_{rec} = 0.03\ B_0 \longrightarrow 0.3\ B_0$

Plasma flows associated with reconnection

Relativistic outflow speed

enhanced inflow speed

current structure aspect ratio ~ 0.1



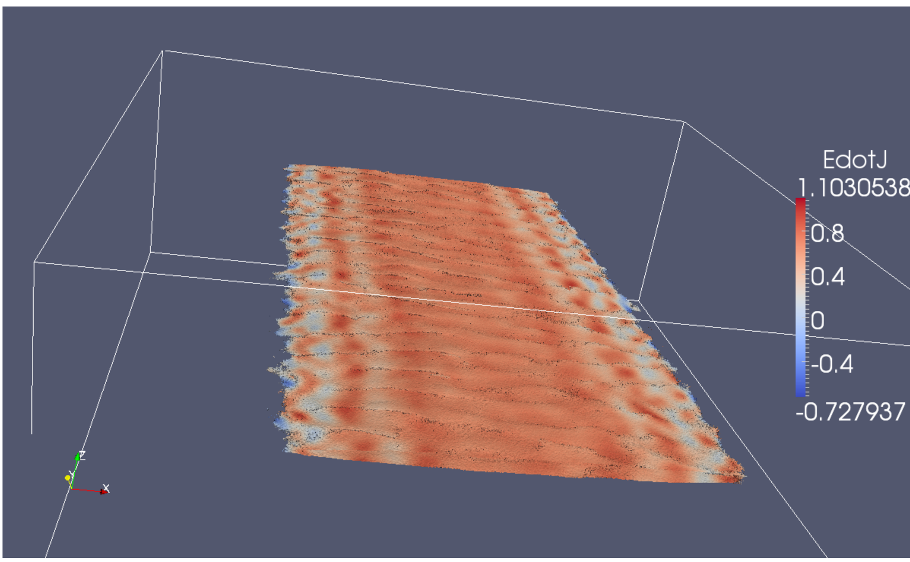
(Liu, Y., GF et al. 14 in preparation)

Energy conversion in the 3D simulation

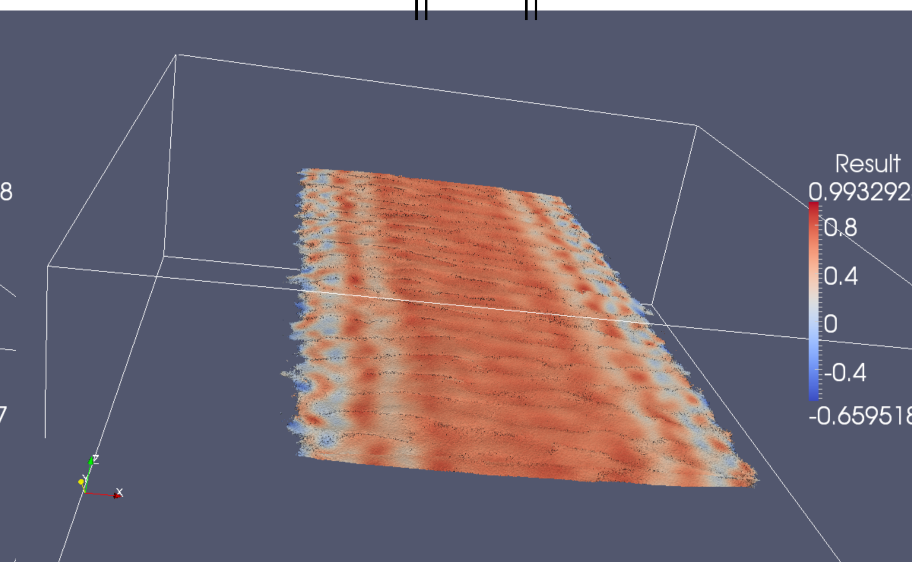
$\Omega_{ce}t = 2550$

Isosurface of current density colored by $J \cdot E$

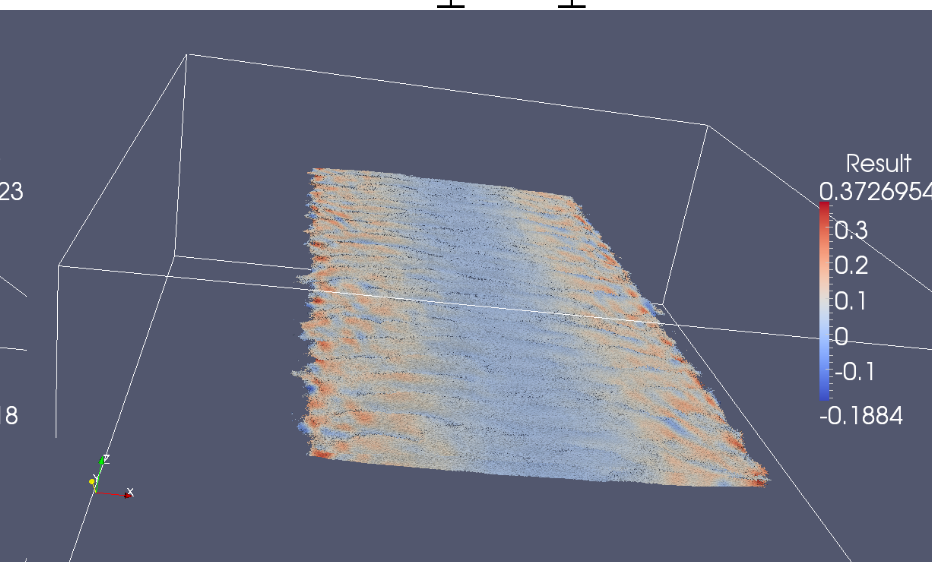
$J \cdot E$



$J_{\parallel} \cdot E_{\parallel}$

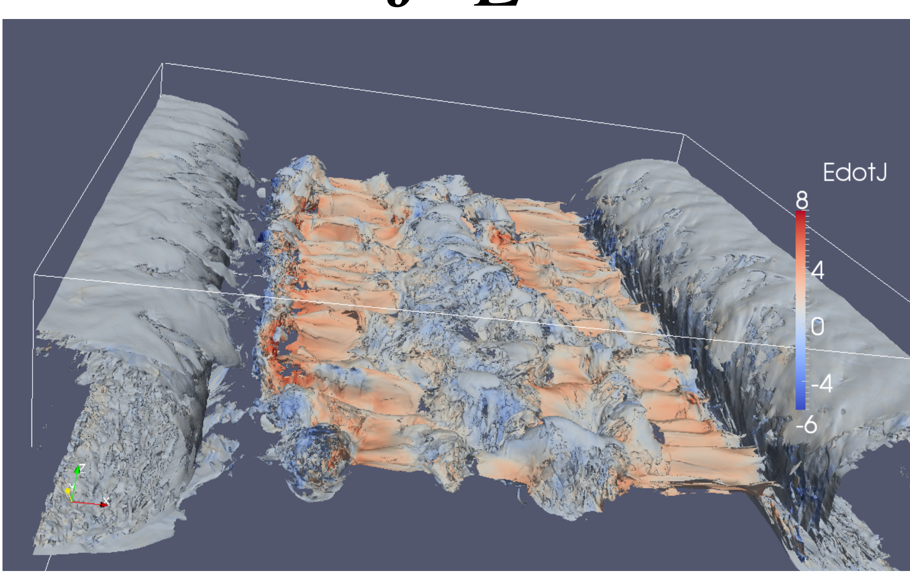


$J_{\perp} \cdot E_{\perp}$

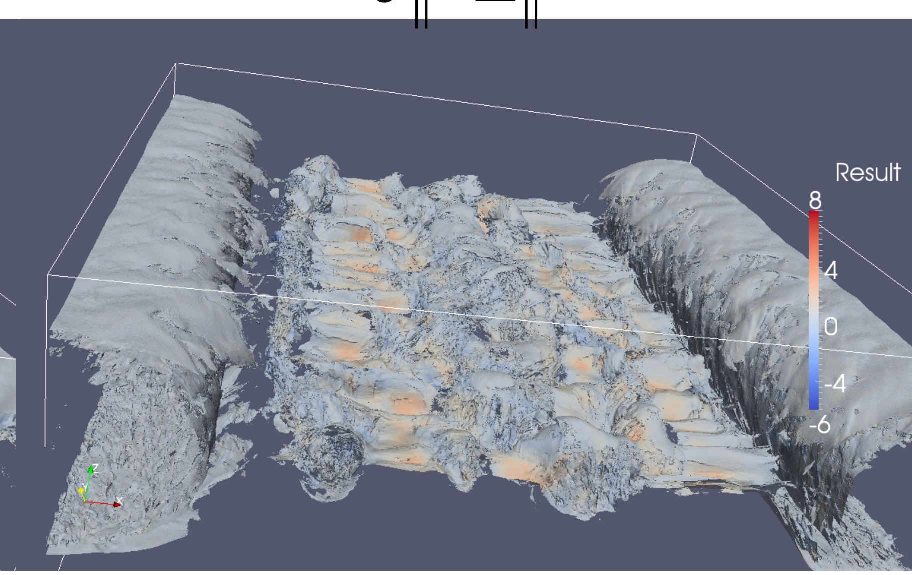


$\Omega_{ce}t = 7140$

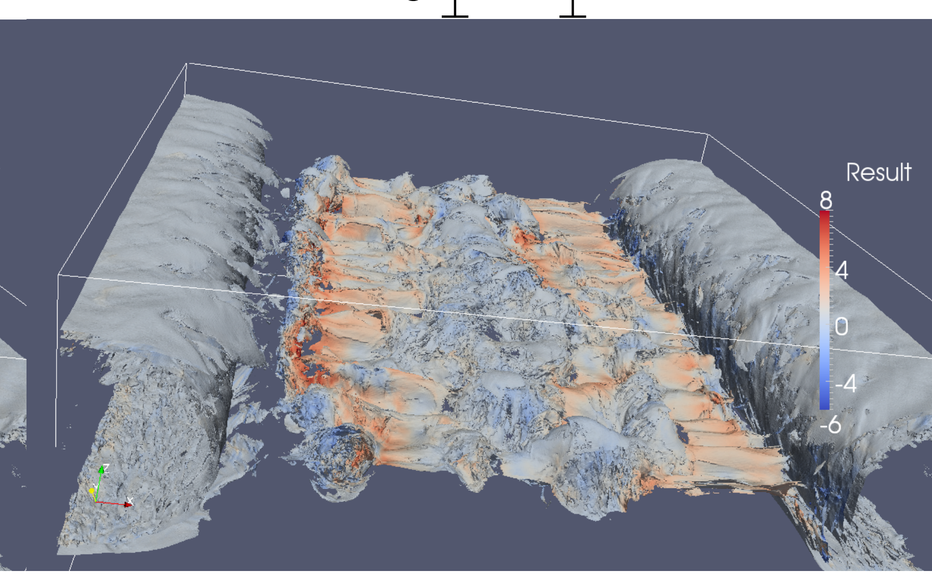
$J \cdot E$



$J_{\parallel} \cdot E_{\parallel}$



$J_{\perp} \cdot E_{\perp}$



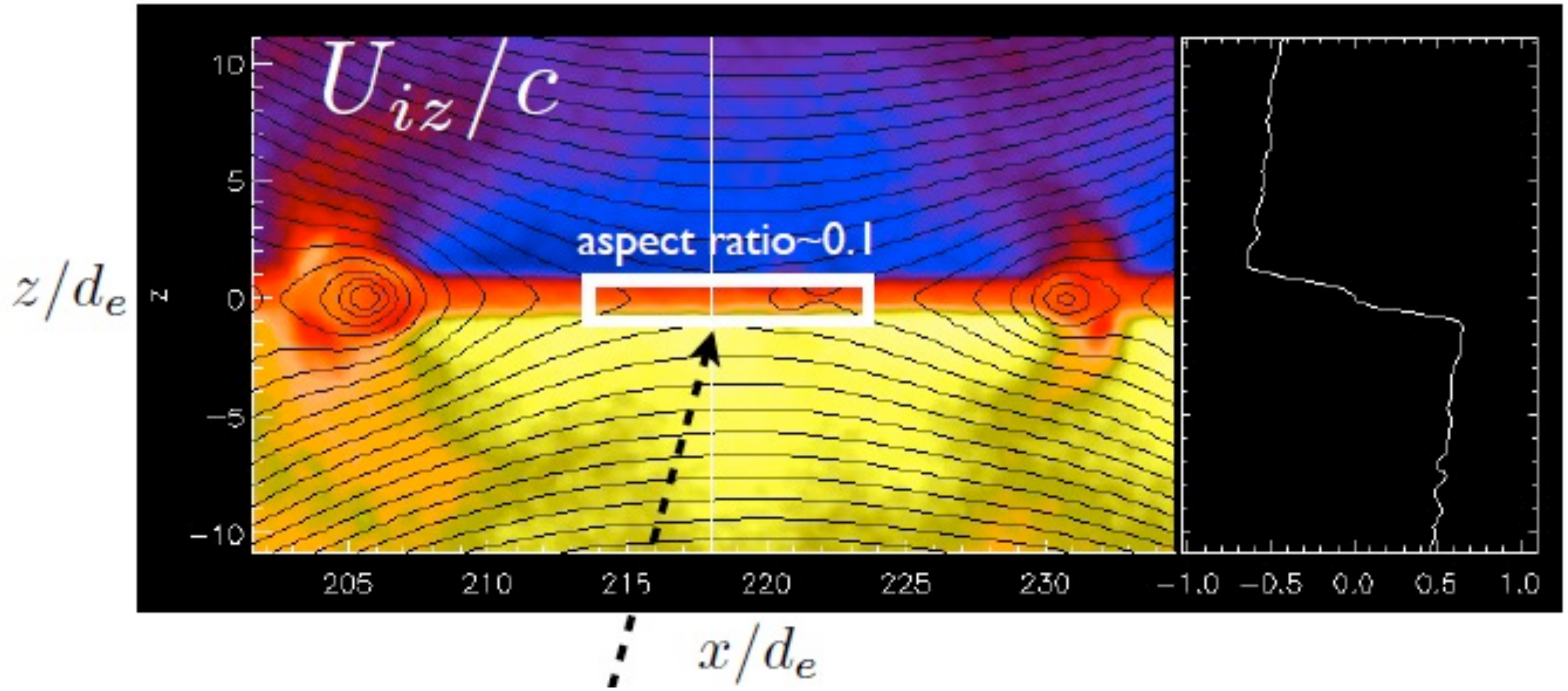
Typical spatial scale di = 5e5 Gamma
ne^(1/2) cm
and time scale t = 1/wpe = 2e-5
ne^{-1/2} s

Magnetic Reconnection Rate

- Lots of secondary islands/3D filamentary structures

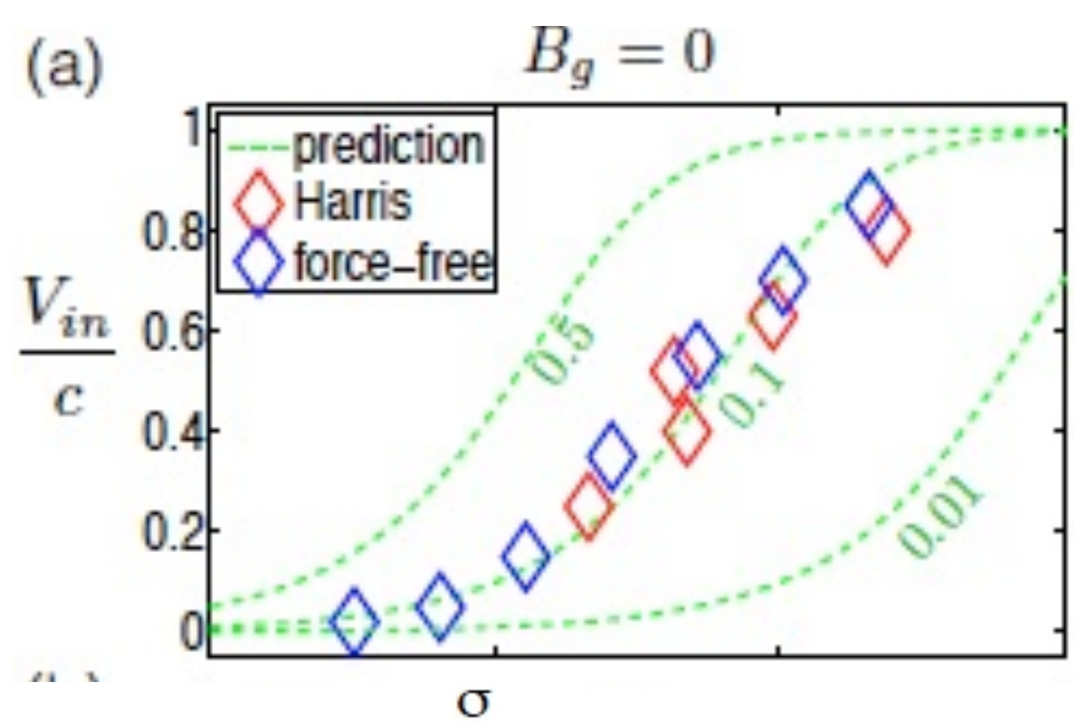
- The rate is enhanced due to relativistic inflow/outflow.

- Current sheet aspect ratio remains ~0.1



nonrelativistic $$R \sim \frac{\delta_i}{L_i}\frac{v_{i,out}}{V_{Ax}} \sim \frac{\delta_i}{L_i} \sim 0.1$$

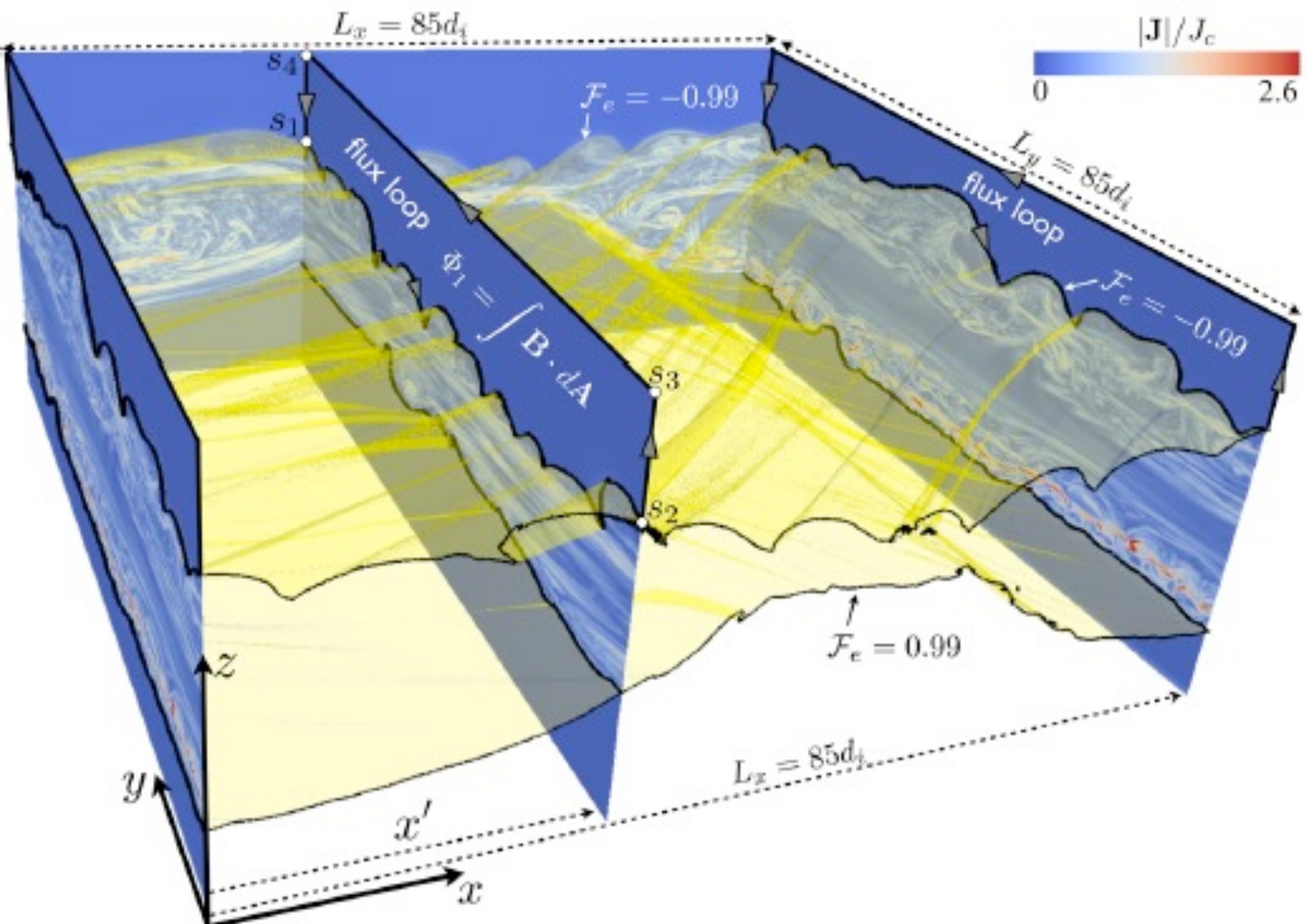
relativistic $$R = \frac{\delta}{L}\sqrt{\frac{1+\sigma}{1+(\delta/L)^2\sigma}}$$



Yi-Hsin Liu et al.
(2014 in preparation)

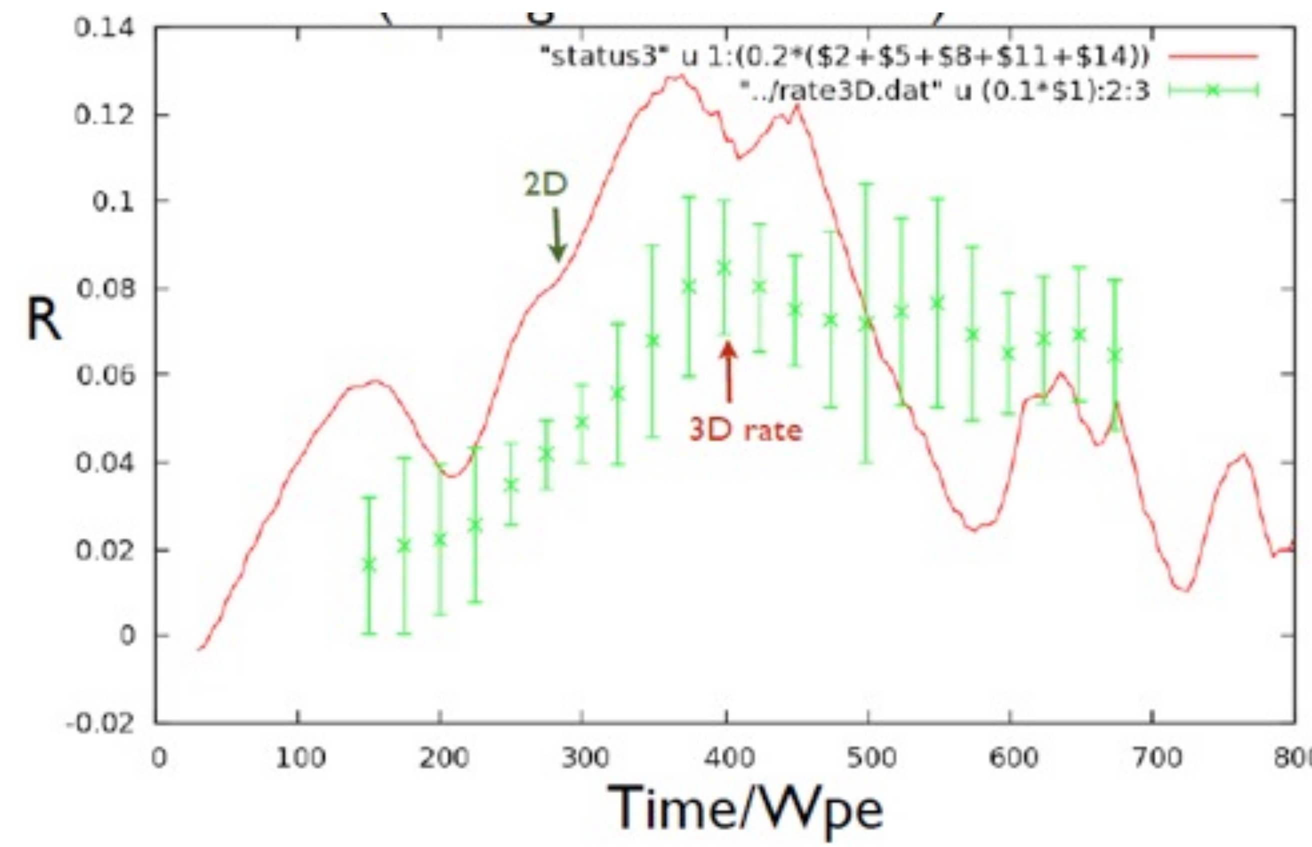
Global rate changes ~10 times:
$E_{rec} = 0.03\ B_0 \longrightarrow 0.3\ B_0$

Magnetic Reconnection Rate 2D vs 3D



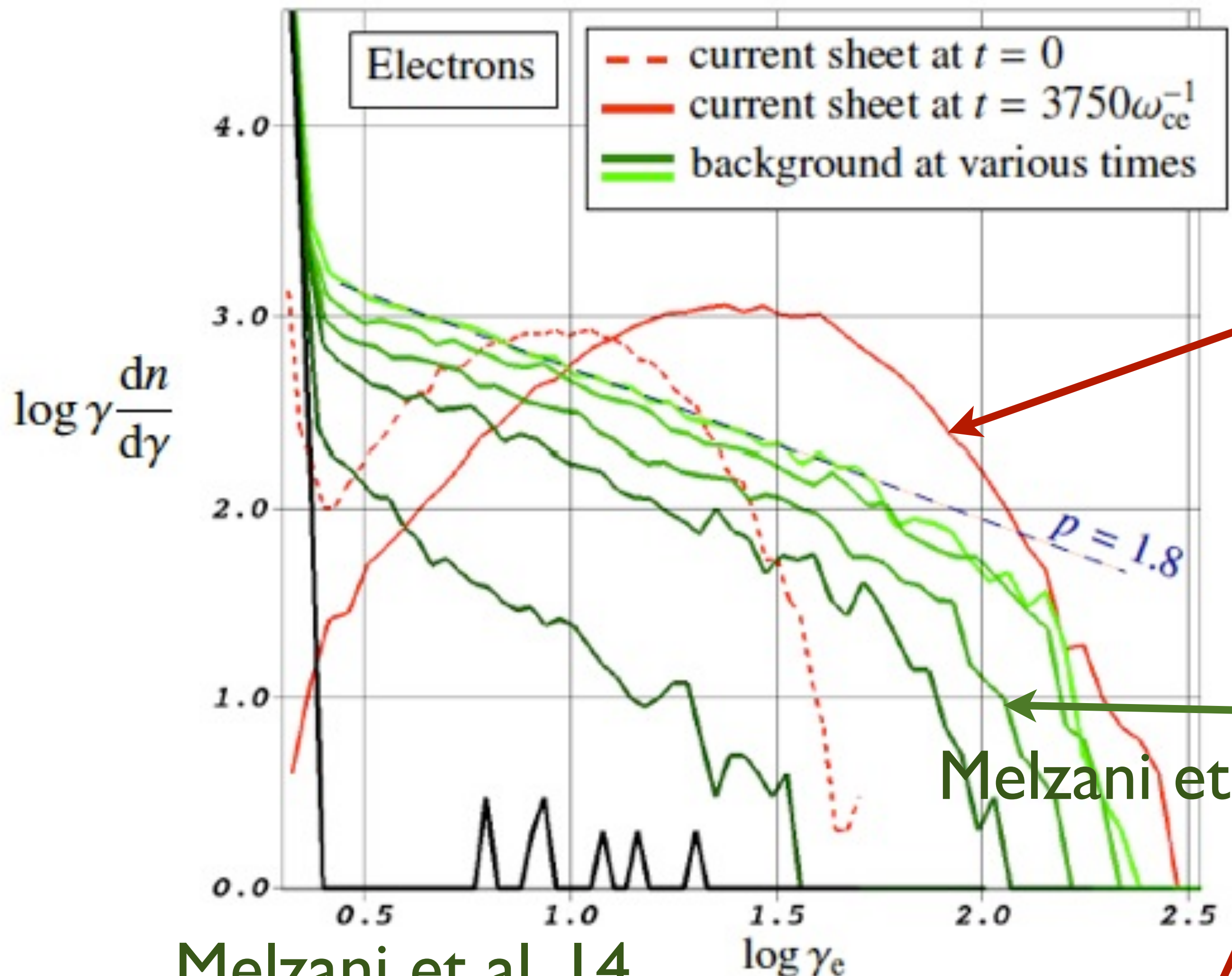
Daughton et al. 2014

The same technique is used for relativistic reconnection



2D and 3D gives similar rate, consistent with nonrelativistic results

The full solution that includes initial current sheet particles



Melzani et al. 14.

Initial current sheet component (heated component)

Injected component (Power-law component)

$$f(\varepsilon,t) = \frac{2N_0}{\sqrt{\pi}}\sqrt{\varepsilon}e^{-(3/2+\beta)\alpha t}\exp(-\varepsilon e^{-\alpha t})$$
$$+ \frac{2N_{inj}}{\sqrt{\pi}(\alpha\tau_{inj})\varepsilon^{1+\beta}}\left[\Gamma_{(3/2+\beta)}(\varepsilon e^{-\alpha t}) - \Gamma_{(3/2+\beta)}(\varepsilon)\right],$$

In the force-free setup $N_0 << N_{inj}$

This explains our simulations well, and is consistent with simulations by Sironi & Spitkovsky 14 and Melzani et al. 14, who used pressure balanced layer.